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Division of Microstructural Sciences
Division des sciences des microstructures

Activities 1985

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Cover: A computed charge density map of an unreconstructed Si(111) surface as might be seen by a scanning tunnelling microscope.

DIVISION OF MICROSTRUCTURAL SCIENCES

Activities 1985

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A. INTRODUCTION

The Division of Microstructural Sciences was started officially in April of 1984, in response to a perceived weakness in the spectrum of the National Research Council of Canada (NRC) activities in the areas of semiconductors and structures made from semiconducting materials. The objective set for the Division is very broad: to carry out research which will add to the understanding of the physics or the resolution of materials problems, in areas of actual or potential relevance to high technology industry. In practice, the activities within the broad mandate are limited by the resources at our disposal, by our expertise, and by our choice to work in collaboration rather than competition with other Canadian laboratories. Within the range of possibilities, choices are made on the basis of the intrinsic importance, technological or scientific, of the proposed project, as perceived by us and the community that we interact with.

In the first year of our existence, we have started three major new projects. By far the largest was the commencement of research into "structures of low dimensionality." This field is vast, and research into it should, perhaps, be viewed more properly as a "program" rather than a "project." It is exciting scientifically and very important technically. It embraces new scientific discoveries such as the Quantized Hall resistance, structures such as superlattices and quantum wells, and devices such as HEMTs (high electron mobility transistors), and promises an almost unlimited scope for discovery and development. Entry into this field requires large facilities and resources for the preparation of the starting (structured) material, its characterization, its subsequent fabrication into suitable "devices" (whether simple or complex), and finally for the testing and analysis of these devices. To gain entry into this field, we needed to acquire some major sophisticated equipment, and this was purchased in our first year. The more notable examples

are a two-chamber molecular beam epitaxy machine, a Philips 430 TEM/STEM electron microscope, and a 15-T superconducting magnet with an associated dilution refrigerator. Additionally, we have also constructed clean-room facilities and acquired routine microfabrication equipment. Last year saw both the installation of this equipment and its successful commissioning. The magnet/dilution refrigerator facility was operational in April and is capable routinely of reaching 15 mK at magnetic fields in excess of 14 T. The 300-kV TEM/STEM facility was also operational in April, and its use in the subsequent nine months has mushroomed to fill virtually all available time; work performed on it is referred to frequently throughout this report. The MBE facility arrived in mid-July and was producing specimens by October. The quality of these specimens improved rapidly, and exciting results are being reported towards the end of the year.

The other two major projects started in our first year, research into ultra-fast processes in semiconductors and the development of a technique for the analysis of trace impurities through laser ionization of sputtered atoms (LISA), have also made good progress. In the first case, the major part of the laboratory has been set up, and work is now in progress on coupled plasmon-phonon modes in binary III-V semiconductors (6a). For LISA, the prototype system is operational and work on semiconductor applications will follow (2d).

In addition to developing facilities started in the first year, we have undertaken the development of a major new facility, the scanning tunnelling microscope (STM). Such an instrument offers the possibility of direct, real-space determination of surface structure, including its non-periodic features, and complements other surface analytical techniques, such as LEED. The project, which involves both the construction of the experimental system and the associated theoretical analyses, is described in Section 5.

The development of these major facilities mentioned above forms an easily perceived measure of the progress of the Division along its new path. What is less readily perceived, particularly to an external observer, is the real change of the interests of the staff, the degree of reorientation of their work, their projects and discussions. A flavour of that may perhaps be obtained through a detailed perusal of Section B, the review of R&D activities, but a true appreciation of the magnitude of change can only be formed through a comparison of this report with those produced two years ago.

The Division has also continued during the last year its efforts to establish collaborative interactions both with industries and with universities; these are listed in Sections C and D. Two examples may be highlighted: the working out of an official agreement with Bell Northern Research (BNR) for collaborative long-term research; and the offer to the Canadian Microelectronic Corporation (of NSERC) of a major contribution of land, building, and use of facilities should they choose to locate their Research Centre in Ottawa, at the Montreal Road site of NRC.

On the organizational side, a slight restructuring has taken place; this is described in Section F. A start was also made towards the relocation of DMS in Building M-50, on the Montreal Road site of NRC. This relocation will proceed in two phases: in 1986, that part of DMS which is presently located in M-36 (the "Physics" Building) will move to existing space in M-50. Also in 1986 a start will be made on an addition to M-50, a new wing, to be completed in three years. Upon the completion of the wing, the rest of DMS, presently located in M-23A, will join the main part of the Division. Preliminary plans for the new wing have already been made.

In conclusion, I should point out that, as before, this report departs in format from that normally used in NRC, in that it groups the description by the field

of research rather than by the administrative section wherein it was carried out. The choice was made for the benefit of the reader, to permit him more readily to pursue his particular interests, and to illustrate the collaborative and interrelated nature of the various activities.

M.J. Laubitz

B. REVIEW OF R&D ACTIVITIES

For the purpose of review, the activities of the Division have been sub-divided into 11 categories. There is necessarily some degree of arbitrariness in these categories and some projects overlap the boundaries. The various activities cross all the administrative boundaries between sections, as do many of the collaborations. Personnel contributing substantially to particular projects are listed in parentheses at the end of each description. The divisional organization and a cross referencing of the personnel is given in Section F.

1. Epitaxial Growth and Thin Films

Epitaxial films of semiconductors can now be deposited with composition changes controlled at the single atomic layer level. Such "microstructured" materials are forming the basis of a whole new generation of microelectronic and microoptical devices. Both fundamental and applied research in this field continue with vigor, and further major advances are anticipated.

Molecular beam epitaxy (MBE) has proved to be a particularly suitable technique for the growth of such epitaxial films for research purposes. For this reason, MBE was chosen as a central element of our research effort in microstructures. Other growth techniques are used when appropriate.

(a) Molecular Beam Epitaxy

The main components of our two chamber (MBE) machine were delivered in mid-July 1985. The first silicon film was grown on September 3 and the first gallium arsenide film on October 29. Despite the time consumed in dealing with many vacuum, mechanical, and electronic failures, 29 Si and SiGe alloy films and 17 GaAs, GaAlAs, and GaInAs films had been grown by the end of the year. The ion doping unit for the Si

growth chamber is due to be delivered February 1, 1986, completing the MBE machine itself.

Most of the equipment for the fast-response characterization needed to guide the film growth has been brought into routine operation. Included are optical and scanning electron microscopy, Hall mobility, current-voltage (I-V), capacitance-voltage (C-V), and resistivity measurements as well as electrochemical C-V profiling and photoluminescence. A double crystal X-ray diffractometer will be added in the next few months.

It is our aim to make the capabilities of the MBE facility available to as many users in the Canadian research community as possible. To this end, during 1985 we initiated collaborative projects with more than 20 research groups in industry, university, and government laboratories (see Section C). Several more are presently being negotiated.

Special mention should be made of our interaction with research groups in Bell Northern Research and Northern Telecom. These have involved literally every member of the MBE Section and too many individual contacts to make listing practicable.

(E.V. Kornelsen)

The compound semiconductor chamber has been used to grow epitaxial films of GaAs, GaAlAs, and thin strained layers of GaInAs on GaAs substrates. The background impurity levels are 1-2 $\times$ 10^{15} cm^{-3} p-type using As_4 as the arsenic source, and ~5 $\times$ 10^{15} cm^{-3} n-type using As_2. Hall effect measurements indicate mobilities of 3 $\times$ 10^4 $cm^2/(V\ s)$ at 77 K for Si-doped samples of GaAs. Photoluminescence of strained layer quantum wells of $In_xGa_{1-x}As$ with $x = 0.15$ have shown that the layers are of good optical quality. These materials are candidates for high speed field effect transistors operating at room temperature.

(W.T. Moore, R. Devine, P. Maigné)

In the Si growth chamber, device quality Si, Ge, and Si-Ge strained layer superlattices have been grown on Si substrates. The major technological problems of controlling crystalline perfection and impurity levels have been overcome. Background impurity levels are typically less than 5×10^{15} cm^{-3} while electron mobilities and crystalline perfection are identical to those found in high quality bulk single crystals. Lattice resolution cross-sectional transmission electron microscopy of Si-Ge superlattices reveals that the heterointerfaces are atomically abrupt.

The recently discovered band gap reduction in Si-Ge strained layer superlattices opens up the exciting prospect of "band gap engineering" where the tunable parameters are strain and x in $Si_{1-x}Ge_x$. Superlattices exhibiting absorption edges at 1.3 and 1.55 μm the transparency wavelengths for silica fibres used in optical communications have been grown and are being characterized as candidates for integrated optoelectronic devices.

(D.C. Houghton, M. Denhoff, J.-M. Baribeau)

(b) II-VI/IV-VI Semiconductors

We plan to grow high-quality epitaxial II-VI/IV-VI alloy semiconductor films for specific applications as photodetectors, and also to explore this very important group of semiconductors. To this end, we are adding to our rf sputtering system the capability of ion-assisted magnetron sputtering and an optical monitor of the plasma. Furthermore, we are assembling equipment to put electrical contacts on the specimens and to measure their dark conductivity and photoconductivity, and their temperature dependence.

(J.G. Cook, M.P. van der Meer, with S.R. Das, Division of Physics)

(c) Thin Film Deposition Using Ion or Fast Atom Beams and RF Magnetron Sputtering

The technique of ion beam milling is well suited to microlithography and electron microscope sample preparation. A modification of this concept has been used to fabricate channel waveguides, sputter thin films of dielectrics and semiconductors. The lack of rf plasma and high vacua during deposition are definite advantages for making clean films. We are setting up to deposit epitaxial layers of Si and GaAs to be used as optical waveguides for nonlinear physics experiments and devices in optoelectronics and all-optical ultrafast signal processors. Some films have also been deposited for use by Northern Telecom and to fabricate fast switches for Bell Northern Research. Epitaxial growth of nonlinear materials for ultrafast $LiNbO_3$-sapphire correlators in fiber-optics systems are also performed with the magnetron system.

(R. Normandin)

(d) Rigid Body Displacements at Epitaxial Interfaces

A detailed understanding of atomic positions at interfaces is necessary for defining the role of interfaces in low dimensional electronic structures. The aim of this program is to determine rigid body shifts and interface atomic arrangements in thin film bicrystals. The work involves convergent beam diffraction and high resolution imaging of atomic positions. The latter technique is supported by computer calculations of structure images. The work is done in collaboration with J. Corbett and F. Boswell of the University of Waterloo, Waterloo, Ontario.

(K. Rajan)

(e) Growth Parameters for MBE Films

The growth of high quality devices by MBE methods is aimed at producing materials with low defect densities. The aim of this program is to systematically study the effect of processing parameters on the

structure of MBE-produced films in collaboration with the MBE group.

(K. Rajan)

(f) Sputtering of Composites

A two-magnetron gun sputtering system has been set up. In collaboration with D. Inglis of the Division of Chemistry, the resistivity of co-sputtered Pb-Ge films was monitored during deposition. The data are presently being analyzed to relate the change in microstructure to the change in percolation threshold as one goes from the 2-D to 3-D conduction regime. D. Houghton is doing the microstructural analysis.

Ta-Al composites have been sputtered onto TEM grids held on a liquid nitrogen stage. The microstructure and properties of these films are being analyzed by R. Timsit at Alcan Laboratories in Kingston, Ontario. They appear to have unique mechanical properties and could lead to new high strength aluminum alloys.

Finally, in collaboration with K. Rajan, titanium silicide layers have been made by rapid thermal annealing of thin films of Ti on amorphous silicon supported on TEM grids. The silicides show preferred orientation and give insight into the mechanism of silicide formation for VLSI contacts.

(D. Landheer)

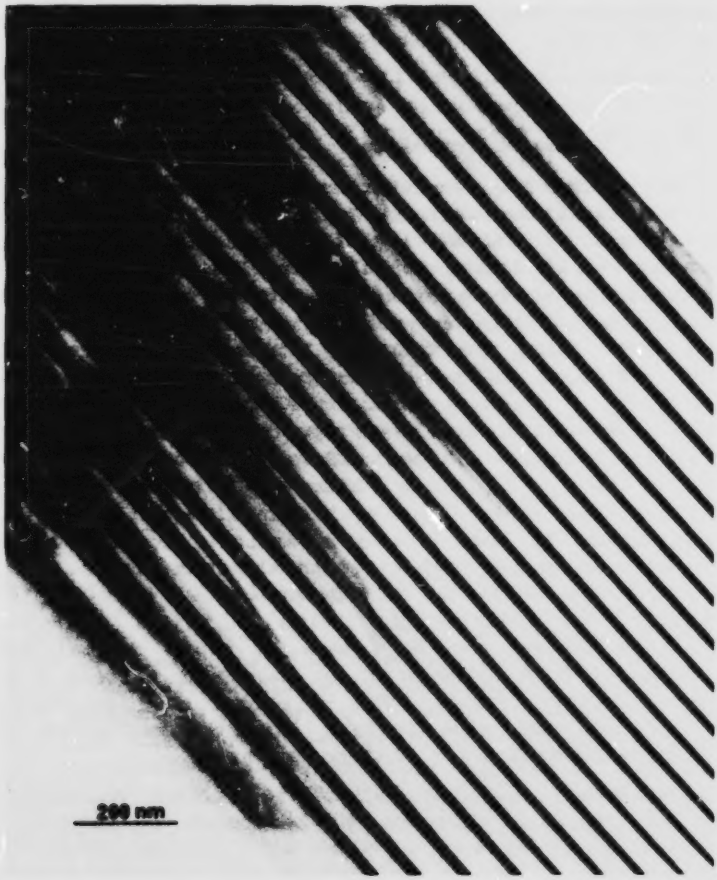

Figure 1 A cross-sectional TEM micrograph of a 20-period Ge_xSi_{1-x}-Si (x = 0.4) superlattice.

2. Materials Characterization and Analysis

Materials characterization and analysis play a vital role in microelectronics. With development of the new, highly structured materials described in Section 1, the analytical requirements are even more demanding. Projects described below include both the in-depth characterization of semiconductor materials, produced, for example, by the molecular beam epitaxy technique and the development of new or modified techniques of analysis which could prove useful to the semiconductor industry in general.

(a) Characterization of Shallow Implants in Silicon using Infrared Total Internal Reflection

The infrared total internal reflection (IRTIR) system set up last year has now been automated. It consists of a collimated CO_2 laser beam which is made to impinge, through a prism, on the interface between an ion-implanted semiconductor wafer and air. The ratio of the reflected and incident intensities is monitored as a function of the incident angle of the beam as the sample is automatically rotated.

We have used this system to determine and compare the properties of annealed silicon wafers which had been implanted with B and BF_2 by Northern Telecom. We demonstrated that it is possible to extract the activated free carrier profile and the mobility of the free carriers in the implanted region using IRTIR. The results indicate that the activation of dopants is greater in the B implanted wafers than in those implanted with BF_2. The activation percentage in the B doped samples ranged from approximately 65% for 1050°C annealing temperatures to 75% for 1150°C anneals. The mobility of the activated carriers in both B and BF_2 samples, annealed at either 1050°C or 1150°C, was the same.

(J.F. Young, B. Kettles)

(b) Determination of Activated Carrier Densities in Zinc Doped InP

In conjunction with people at Bell Northern Research, we are investigating the potential of Raman scattering as a means to determine the activated carrier density in the near-surface region of zinc diffused InP. The near-surface region is difficult to probe with conventional electrical techniques, while Raman scattering is especially sensitive to the region within ~3000 Å of the surface. The free carrier density will be inferred from the energies of the coupled plasmon-longitudinal optic phonon modes near the surface. Information as to the thickness of the depletion region can also be extracted using this technique.

(J.F. Young, B. Kettles)

(c) Photoluminescence for Impurity Analysis

Photoluminescence spectroscopy is a proven technique for the analysis of impurities in semiconductors and for quantifying the dopants deliberately introduced. This technique is used routinely during semiconductor growth and preparation as a check on the quality and suitability of the material. Before the technique can be applied, however, the basic physics in relation to the luminescence properties of a specific semiconductor must be understood. The equipment needed to carry out fundamental research into the photoluminescence properties of a semiconductor at low temperatures and in high magnetic fields has recently been commissioned. The first measurements are being performed on nominally pure epitaxial Si samples grown by the MBE Section to characterize the "background" impurities.

(D.J. Lockwood, H.J. Labbé)

(d) Laser Ionization of Sputtered Atoms

An instrument has been built for development work on a relatively new technique for the analysis of trace impurities or dopants in semiconductors. This is called laser ionization of sputtered atoms (LISA). A widely

used technique of analysis is secondary ion mass spectrometry (SIMS), where material is mass analyzed after being sputtered from the surface as ions by an energetic primary ion beam. As the surface is eroded, a depth profile is obtained. SIMS has been the subject of a fundamental investigation in the Division in the last few years. It has great sensitivity but is difficult to make quantitative because ion yield is very dependent on the chemical nature of the matrix. The new technique involves ionization of sputtered neutrals using a high power pulsed laser. The neutrals are more abundant than ions and their emission is much less matrix-dependent. Ionization occurs via a multiphoton process. Mass analysis is carried out using a time-of-flight spectrometer. Additional specificity can be obtained by using a dye-laser tuned to the resonance for one particular species of impurity. The prototype system is operational. The ion optics and high-speed detection circuitry are being optimized. Work on semiconductor applications will follow.

(P.H. Dawson, J.F. Young, S. Rolfe, G. Richardson)

(e) Evaluation of Implanted Silicon Wafers using Four-Phase Ellipsometry

This project, being done in collaboration with Northern Telecom, is now well-established and is yielding technologically important results. The usual techniques used to measure the doping density and profile of B or BF_2 implanted in Si are either quite time-consuming, destructive in nature, or in the infrared part of the spectrum. By modifying a standard research ellipsometer to use He-Ne light and 0.83 μm light from a solid state AlGaAs laser we can now characterize dose and doping profile of BF_2-Si wafers. By making a computer model of the ellipsometric parameters versus implantation energies and dose we obtain a quick and easy nondestructive method of measurements with a simple instrument already available in most semiconductor manufacturing establishments.

(R. Normandin, M. Simard-Normandin, Northern Telecom)

(f) A New Nondestructive Method to Extract Profile Measurements in Diffused Waveguide Devices

Now that ultrafast optoelectronic components based on $LiNbO_3$ waveguides have become commercially available there has been renewed interest in a nondestructive evaluation of their index profiles. Each waveguide fabricated by diffusion in the $LiNbO_3$ is slightly different due to the statistics and reproducibility of the diffusion process. Existing analytical techniques are quite destructive (i.e., breaking the waveguide, sputtering it away, electron bombardment to extract the X-ray emission of the diffused metal, etc.). We have developed a new technique to measure the doping profile of such waveguides by measuring the cross section of the convolution of two oppositely propagating modes in the nonlinear $LiNbO_3$ guide as a function of the guided light wavelength. A computer program then extracts the refractive index profile at the interface.

(R. Normandin, B. Kettles)

(g) Evaluation of Implanted Silicon Wafers using Photoacoustics

A short pulse of UV light from a nitrogen laser focussed on the surface of a Si wafer is used to generate a pulse of acoustic phonons. We can then measure their velocity by light scattering from a HeNe CW probe a short distance away. We are now trying to model the change of velocity due to the implantation damaged layer in unannealed wafers in relation to the received dose and penetration depth. This would be an extremely quick, go/no-go measurement suitable for a production line environment.

(R. Normandin)

(h) Extended Energy Loss Fine Structure Analysis (EXELFS)

The study of interfacial electronic behaviour of low

dimensional electronic structures requires an experimental means of monitoring structural and electronic information with high spatial resolution. Extended Energy Loss Fine Structure Analysis (EXELFS) using a transmission electron microscope (TEM) allows us to achieve this experimentally. At present we are exploring the potential advantages of high voltage EXELFS over conventional 100 kV studies. Software has been developed to extract the extended fine structure from the energy loss spectrum. Theoretically the Fourier transform of the processed spectrum gives the relative positions of the scatterers in the sample. This technique successfully applied to the X-ray signals (EXAFS) is relatively new for the electron spectrum and its usefulness is still to be demonstrated; if successful the technique has direct application to the analysis of the layers grown by the MBE Section.

(K. Rajan, P.B. Sewell, A. Delâge)

(i) Quantitative High Voltage X-ray Microanalysis

At higher voltages, X-ray microanalysis has some potential advantages such as reduced beam broadening and improved X-ray production efficiency. This program has been established to experimentally measure parameters needed for quantitative X-ray microanalysis at 300 kV. Collaboration occurs with G. L'Espérance of the École Polytechnique, Montreal, Quebec.

(K. Rajan, P.B. Sewell)

(j) Quantitative Electron Energy Loss Spectroscopy (EELS) at High Voltages

This study is to measure parameters needed for quantitative microanalysis by Electron Energy Loss Spectroscopy (EELS) at 300 kV. We are defining experimentally increases in useful sample thicknesses for EELS from 100 to 300 kV and partial ionization cross-sections at 300 kV. We are collaborating with T. Mallis,

Energy, Mines and Resources Canada (EMR), and R. Egerton of the University of Alberta, Edmonton, Alberta.

(K. Rajan, P.B. Sewell)

(k) Weak Beam Imaging of Coherent Interfaces

Weak beam microscopy is a strain sensitive high resolution imaging technique. We have just completed a study of the role of weak beam microscopy in examining dislocation interactions with coherent interfaces in metals. This work is now being extended to study artificially produced coherent interfaces in low dimensional electronic structures such as strained layer superlattices.

(K. Rajan, P.B. Sewell)

(l) Electron Channeling Enhanced Microanalysis

The variation of the characteristic X-ray emission from a thin crystal with crystallographic direction of the incident electron beam can be used to determine the crystallographic position of atoms with similar atomic numbers and low concentration of atoms. We are attempting to apply this technique to study dopant distributions in semiconductors. The voltage dependence of this effect is also being studied both experimentally and theoretically.

(K. Rajan, P.B. Sewell, G. Aers)

(m) Surface Analysis in the TEM

Due to the improved vacuum conditions in electron microscopes, there has been a revival in the field of imaging solid surfaces using forward scattered electrons. Along with imaging we are studying the use of microanalytical techniques such as microdiffraction and EELS to study crystal surfaces. As part of this program we have installed the first high resolution diffraction stage in a 300 kV TEM.

This facility is being used in a collaborative program with the MBE group to study the structure and contamination following various cleaning procedures of silicon substrates. A study of epitaxial layers produced by various deposition techniques on gallium arsenide substrates is being pursued with the Chemical Physics Section of NRC.

(K. Rajan, P.B. Sewell)

(n) Electron Optics in Microscopy

From our experience with the LaB_6 source in the new EM430 TEM/STEM it is apparent that a detailed understanding of the performance characteristics of this source is lacking. Discussions with the designers of this microscope at the Philips Development Laboratories in Eindhoven have confirmed this conclusion. Electron optical characterization of the electron gun is being undertaken to identify the optimum performance parameters. We have programmed a model to describe accurately the emission of a conical cathode with a finite tip radius. This double geometry is responsible for particular effects in the beam shape and the model positively shows their causes.

The electron energy loss spectrometer (EELS) on the microscope is being used for this study. A comparison of the use of tungsten and LaB_6 as electron sources is being undertaken. The work is being done in collaboration with other microscope laboratories in NRC and EMR. Detailed understanding of these phenomena is necessary to achieve the ultimate resolution of the microscopy without excessive periods of gun stabilization and for obtaining improved resolution in fine structure analysis by EELS.

A new project using LaB_6 as an electron source was initiated at the request of AECL Commercial Products of Kanata, Ontario, to help resolve a serious problem which has developed in the operation of their 25 MeV linear accelerators currently in commercial use. A

unique directly heated "linear" LaB_6 source has been developed and tested in an accelerator at Kanata. Due to the success of this prototype and the requirement for immediate commercialization of this filament, it has been necessary to collaborate with a company in the United States to provide the next generation of these filaments. Satisfactory long term performance of the filaments can be predicted from the experimental data but will have to be established within the operating environment of the linear accelerators. Computing of emission properties of the gun has been undertaken.

Work has been conducted with Vickers Instruments in Ottawa to utilize the suppressed emission or coated LaB_6 micro-flat cathode in their latest generation wafer inspection electron microscopes. This novel cathode, developed earlier at NRC, is now the standard source used in the commercial production of their latest, successful electron microscope.

(A. Delage, P.B. Sewell)

Figure 2 Plan view of a TEM micrograph showing a misfit dislocation network on a Ge_xSi_{1-x} (x = 0.4) superlattice.

3. Microfabrication

The semiconductor materials that are grown and characterized must be processed to provide either experimental devices or the particular structures that are required for further scientific research on their physical properties. The Division is trying to build up a capability in this area but at present this is quite limited and we will also depend on outside expertise in the near term.

(a) The Microfabrication Facility

The microfabrication facility is nearing completion after a setback due to a fire. A new mask aligner, ovens, photoresist spinner, cleaning lines, and wet etching facilities all await installation. A five-hearth E-beam evaporator has been built and tested, and an oxygen plasma etcher for stripping photoresist awaits testing.

We have photolithographically defined Schottky barriers and ohmic contacts deposited by E-beam evaporation onto silicon wafers, and performed measurements on a new computer-controlled IV-CV profiler. We will be processing Si-Ge and GaAs-GaAlAs wafers produced by the MBE group. Initial efforts are concentrating on producing Au-Sb ohmic contacts on Si-Ge superlattice structures.

While awaiting reconstruction of the new facility, device processing has continued in the old microlithography room. An HMDS-vapour prime oven and a temperature controlled hot plate for photoresist baking have been introduced. We have learned to electroplate 2-μm-thick lines into photoresist channels 4 μm deep to create microwave electrodes and contact pads for wire bonding. A new thermosonic wire bonder has been tested and is in use.

(D. Landheer, M. Buchanan, E. Vilks)

(b) Lithium Niobate Structures

Work has continued on a waveguide Mach-Zehnder interferometer with unique travelling wave electrodes that we are making for an electric field sensor in collaboration with A. Podgorski and J. Chrostowski of the Division of Electrical Engineering. A design was generated on a graphics terminal using the KIC software on the VAX. A file was then sent on magnetic tape to a company for generation of E-beam masks with a 0.25-μm step size. An initial device has been fabricated and is undergoing optical testing. We have made a mount and leadouts and will assemble the device for electrical testing.

A SIMS-Auger study of Ti diffusion in lithium niobate has been completed and awaits publication. We have shown that Na and Si impurities introduced during diffusion may account for the differences in published titanium diffusion constants. This work was done in collaboration with D.F. Mitchel and G.I. Sproule in the Division of Chemistry.

As a result of our efforts on lithium niobate, we are in a position to make various integrated optical devices for optical signal processing. We have diffused several single-mode slab waveguides for use at BNR and will participate in the processing of some channel waveguide couplers and modulators for R. Giles at BNR in Edmonton, Alberta.

(D. Landheer, M. Buchanan, E. Vilks)

(c) X-ray Source Development

The program of development of a plasma X-ray source for sub-micron lithography based on the Spherical Pinch concept has been vigorously pursued in the past year both from the engineering side and the analytical side. Most of the components of the machine have been acquired and partially assembled, such as the condenser banks, trigger units, delay generator, high voltage switches, calibrated X-ray detector, etc., and

the only remaining piece, the spherical pinch head, is being manufactured in the workshop. At the same time, the analytical work has continued and it has confirmed that the radiation processes from the plasma should proceed with high efficiency, namely 91% of the plasma energy should be converted into radiation energy. We are now setting up a computer program for the numerical simulation of the entire phenomenon, in order to optimize the parameters of the machine, especially in terms of the X-ray output suitable for microlithography.

Two companies have expressed an interest in the development of the machine. They are MacDonald Dettwiler of Richmond, British Columbia, and Lumonics of Kanata, Ontario.

Initial steps for collaborative work in this field have been taken with the Department of Physics of the Old Dominion University, Norfolk, Vermont, following their interest recently expressed in plasma X-ray generation. The collaboration has started in the form of an exchange of information, and now is taking shape in the form of assistance to us in carrying out the simulation of the entire phenomenon through the national computer facility of Livermore, to which they have access.

Our collaboration with the Department of Physics of the University of Western Ontario, London, Ontario, has continued in the past year, mainly in the form of an exchange of information and assistance. Our expertise in plasma physics is beneficial for them in developing a microwave plasma light source for surface layer processing of silicon and silicon-metal alloys. At the same time, the development of the Spherical Pinch X-ray source will be beneficial for both groups for future studies of materials.

(E. Panarella, V. Guty, P. Savic)

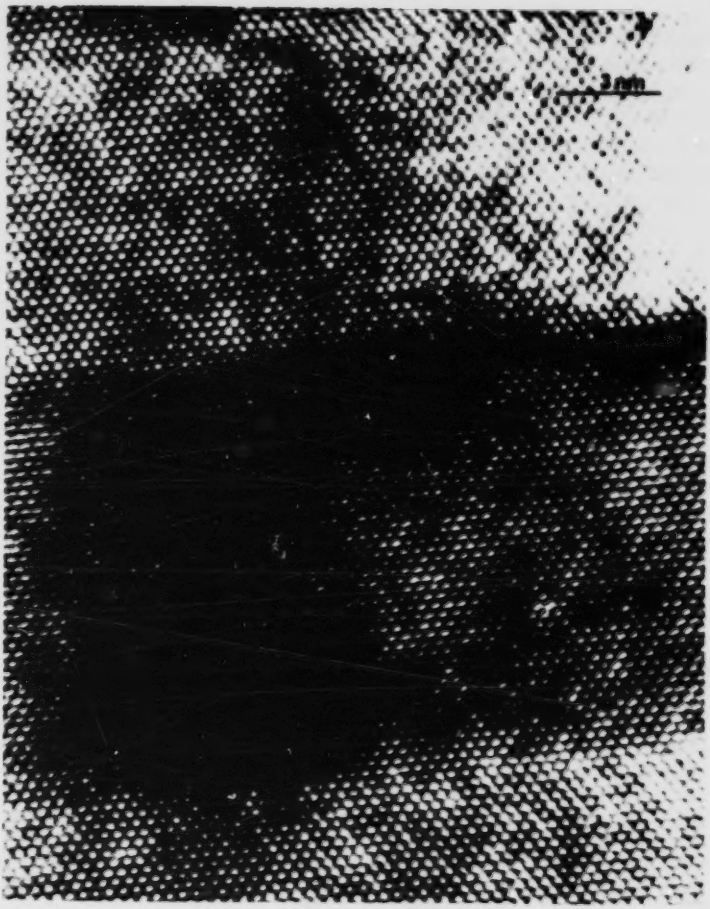

Figure 3 Lattice image of a 10 nm GaAs single quantum well entrained in AlAs grown by MBE (crystal growth courtesy of T. Springthorpe, BNR).

4. Reduced Dimensionality Physics

The capability of producing new semiconductor materials which are "engineered" to have a desired set of physical properties opens up totally new areas of physics, closely related to new electronic devices. One example is the production of layered semiconductor materials where the electrons are constrained to move in two dimensions. New physical phenomena, the quantum Hall effect and the fractional quantum Hall effect, were recently discovered. Similar semiconductor structures are already finding application in devices such as High Electron Mobility Transistors (HEMTs).

(a) Quantum Hall Effect

The quantum Hall effect was discovered five years ago by Klaus von Klitzing, who was awarded the 1985 Nobel prize in physics for this fundamental work. When a silicon MOSFET transistor or a semiconductor heterostructure is studied at very low temperature and high magnetic field, the charge carriers move only in a two-dimensional plane at the interface; measurements of longitudinal and transverse resistance (Hall measurements) yield a surprising quantization depending only on Planck's constant and the charge of the electron. The integer and fractional quantum Hall effects are not only important discoveries in solid state physics but also have practical applications for semiconductor devices and electrical standards.

In the last year, the quantum Hall effect has been used to establish a quantum standard of resistance at NRC. Precision measurements to 1 part in 10^7 were carried out on GaAs-GaAlAs heterostructures in a 150-kG superconducting magnet at 1.5 K. This precision will be further enhanced in the coming year to ~1 part in 10^8 using cryogenic comparator and SQUID detection techniques. High precision measurements were also performed to shed some light on a fundamental linear relationship between Hall and longitudinal resistances as a function of temperature in the quantum limit.

(M. D'Iorio, D. Brown, B.M. Wood and L. Nadon, Division of Physics)

Most of the interesting solid state physics in two-dimensional systems lies in the very low temperature regime. A ^{3}He-^{4}He top-loading dilution refrigerator was put into operation this summer and works in tandem with the 150-kG magnet to produce 20 mK $<$ T, $<$ 4.2 K and 0 $<$ B, $<$ 150 kG. This is a unique facility in Canada. In collaboration with the Philips Research Laboratory, England, the effect of electric fields on the magnetotransport properties of GaAs-GaAlAs heterostructures was investigated.

(M. D'Iorio, D. Brown, B.M. Wood, Division of Physics, J.J. Harris and C. Jui, Philips)

The capability of performing high precision measurements in the 150 kG - 20 mK setup was exploited in the study of Na^+-doped Si-MOSFET. In this collaboration with the Naval Research Laboratory, Washington, DC, the effect of the interface charge on the quantization of Landau levels was investigated. It is important to evaluate experimentally the effect of impurities on the quantum Hall effect and check some current theories.

(M. D'Iorio, B.M. Wood, Division of Physics)

At the moment, a study of 2-D holes in p-type GaAs-GaAlAs is underway. In particular, the temperature dependence of the magneto-transport properties in the low field regime and the behaviour of the activation energy of the fractional quantum Hall effect at very low temperature are under investigation. This work is a collaboration with IBM Yorktown Heights.

(M. D'Iorio, A. Sachrajda, B.M. Wood, Division of Physics, E. Mendez, IBM)

(b) Two-Dimensional Electron Gas (2DEG) Theory

As part of an ongoing program we have continued our theoretical studies of Two-Dimensional Electron Gas (2DEG) in a strong magnetic field. The topics investigated include cyclotron resonance, thermodynamic properties, shallow donors, excitons, and the fractional quantum Hall effect (FQHE).

We developed a theory of the collective excitation spectrum of the 2DEG in the FQHE regime in analogy with Feynman's theory of liquid helium. The idea is to model the dynamic structure factor $S(k, \omega)$ using a single mode approximation for the magnetoplasmon. This model was also extended to relate the conductivity in the FQHE regime to the excitation spectrum modified by impurities.

Hartree-Fock theory of the response function of the 2DEG for filled Landau levels was extended to the case of partially filled levels; a simple model for inclusion of electron-electron interactions was developed.

We have proposed an explanation for the splitting in the observed cyclotron frequency by considering how impurities would modify the $q \to 0$ limit of the excitation spectrum using the Hartree-Fock theory of partially filled systems in the FQHE regime.

Hartree-Fock theory of the 2DEG at integer filling factors was used to calculate thermodynamic properties. Then, using a proposed one-to-one correspondence, we examined the thermodynamic properties of fractionally filled systems. This has led to definitive results which can be used as a test of current theories of FQHE. Thus, for example, the heat capacity at filling factor $\nu = 1/3$ should be a minimum (for small variations of ν about 1/3) at very low temperatures, but would become a maximum at the high temperature end of the FQHE regime.

Qualitatively new physics has been predicted for the FQHE of many-conduction-band-valley semiconductors involving collective modes associated with electron-valley population.

(G.C. Aers, M.W.C. Dharma-wardana, A.H. MacDonald, H.C.A. Oji, D.S. Ritchie, Division of Physics)

(c) de Haas - van Alphen Effect in Two-Dimensional Electron Systems

There is considerable interest in measuring the field-dependent magnetization in two-dimensional electron

systems. Preliminary trials have been made toward the development of a suitable torque magnetometer.

(I.M. Templeton)

(d) Superlattices

One consequence of the additional periodicity arising from a superlattice is the phenomenon of "folded phonons." Calculations have been carried out for phonons in $Si_{1-x}Ge_x/Si$ superlattices with a view to interpreting light scattering experiments from MBE-grown samples made at NRC. These systems are interesting since they can involve effects arising from superlattice effects, lattice strain, composition variation, etc.

(M.W.C. Dharma-wardana, D.J. Lockwood)

(e) Spin Density Waves in Quasi-one-dimensional Systems

Quasi-one-dimensional (Q-1D) electron systems occur in a large number of organic materials and in a much smaller number of inorganic compounds such as niobium or tantalum triselenide. In such systems and as the temperature is lowered, the independent electrons of a Q-1D metal usually form an electron crystal state, with the crystallization being one of either periodic charge density or periodic spin density. The spin density wave (SDW) is more complicated than the charge density wave (CDW), particularly in interaction with light, because the even-order harmonics of a SDW have charge-density character. The SDW is in a sense a mixed state whereas the CDW is not.

We have developed a theory for interaction of far-infrared light or microwaves with a SDW electron crystal in a Q-1D electron system. Charge density harmonics of the SDW interact with and distort the host crystal lattice. Relaxation effects in this cause far-infrared and microwave resonant absorption. We are developing a theory for this so that recent gigahertz experiments (UCLA-Santa Barbara group) can be interpreted in terms of properties of the SDW.

(E.W. Fenton, G.C. Aers)

Figure 4 Cross-sectional TEM micrograph of GaAs grown directly on <100> Si by MBE. Note the high dislocation density at the GaAs/Si interface and the distortion of the AlAs/GaAs superlattice.

5. Surface and Interface Studies

With the advances in materials preparation and the ever-decreasing size of electronic devices, surfaces and interfaces can become dominant in deciding electronic properties. A variety of experimental techniques are employed in the study of surfaces in an attempt to increase our knowledge of surface geometries on an atomic scale. Some novel surface sensitive techniques are being developed. Interfaces in thin film multilayer structures are extensively investigated.

(a) Scanning Tunnelling Microscopy

This method offers, for the first time, the possibility of direct, real-space determination of surface structure including non-periodic structures. It complements other techniques presently used by DMS such as LEED, Raman spectroscopy, atomic diffraction, and IDAP, which obtain structural information averaged over a large area. A number of members of DMS are collaborating theoretically and experimentally in this project which began in September 1985.

The technique produces a contour map of the surface by scanning a metal tip in two dimensions above the sample while a servo drive moves the tip up and down to keep the tunnelling current constant. For clean surfaces in ultrahigh vacuum (UHV), lateral resolution of 0.3 nm and vertical resolution of 0.01 nm have been obtained. The technique has also been used successfully in air at atmospheric pressure, in liquid nitrogen, in oil, and in helium vapour at 4.2 K.

We plan to study clean surfaces, adsorption structures, and thin films in UHV with LEED and AES available to characterize the surfaces. A sample transfer system is planned to avoid baking each time a sample is introduced.

Image processing aspects are being developed concurrently with construction of the equipment and direct comparisons with theoretical predictions will be made on-line.

(R.A. Armstrong, J. Hulse, D. Blair)

(b) Scanning Tunnelling Microscope: Theory

We investigated the effect of lattice vibrations on images obtained with the Scanning Tunnelling Microscope (STM). The motivation for this study was simply that at room temperature the root-mean-square displacements of surface ions can be much larger than the vertical resolution obtainable with this remarkable instrument. The transit time for an electron tunnelling across the vacuum gap of a STM is orders of magnitude smaller than the characteristic timescale for lattice vibrations, which, in turn, is many orders of magnitude smaller than the response time of the feedback mechanism that controls the width of the gap. Hence, the instrument averages over a vast number of ionic configurations of the sample and probe, giving strong preference to those which minimize the vacuum gap. Thus, the effective probe-to-sample distance is smaller than that determined from the average ion positions. We showed that the difference is proportional to the mean-square-fluctuation $\langle \delta^2 \rangle$ in the probe-to-sample distance. Fitting a static theory to experimental results can thus lead to errors of interpretation, particularly if $\langle \delta^2 \rangle$ varies significantly over the sample surface. An interesting possibility is that the surface contour maps produced with the STM could show sharper structure at higher temperature.

(R. Leavens, G.C. Aers)

(c) Raman Spectroscopy

Raman spectroscopy is a vibrational spectroscopy which reveals many of the fundamental modes of vibration of the substrate under study. While of inherently low sensitivity, it exhibits sufficiently high resolution

and range of accessible vibrational frequencies to recommend it as a technique equal in value to any other for studying vibrations. The vagaries of purchase and construction of the spectrometer have passed into history and initial testing and calibration completed so that the actual measurement of surface Raman spectra can now begin.

These first serious measurements are now being carried out on a palladium single crystal on which layers of adsorbed gas are formed by exposure to carbon monoxide, oxygen, and benzene vapours. These chemisorption systems have been chosen for the broad range of knowledge which has already been amassed for them. This will establish a high level of confidence in the interpretation of the first Raman spectra for these systems. These measurements will uncover details of adsorption site and bonding which have heretofore remained in the realm of speculation. Armed with this knowledge, it will be possible to draw important conclusions vis-à-vis the chemical activities that characterize these cases of chemisorption.

(J. Hulse)

(d) Low Energy Electron Diffraction

Low energy electron diffraction (LEED) data contain, in principle, all of the geometric information that one could wish to gather from the surface of a material. However, to extract this knowledge is a formidable, computationally intensive exercise. Moreover, the analysis of LEED has suffered until recently under a paucity of reliable experimental data.

Traditionally, these diffraction data are obtained as a pattern of spatially resolved diffraction spots whose geometry is used to deduce the symmetry of the net of surface atoms complemented by a set of profiles of spot intensity vs. incident electron beam energy which is "analyzed" by a fitting procedure wherein a surface geometry is guessed at and then the difficult

computations alluded to above are performed to produce intensity profiles for comparison with experiment. The weakest link in this chain is actually not the computation, but rather the difficulty of producing a large number of experimental spot profiles during an experimenter's lifetime.

The recent advance in data acquisition rates has been achieved with the aid of modern video technology which permits intensity profiles of entire patterns and not just individual spots to be recorded on magnetic tape. Thereafter the spot profiles may be extracted at leisure and in much greater numbers. This methodology has been further advanced in the LEED project here by the use of video image digitizer which can "grab" an entire picture as quickly as the video camera produces it and optionally add it to previously acquired images thereby improving the image quality by averaging. This represents a substantial improvement over direct storage onto magnetic tape which process actually degrades an image significantly. The collection of experimental data has been entirely automated and is now finding application to those same chemisorption systems that are being studied by Raman spectroscopy.

(J. Hulse)

(e) IDAP Incidence Dependant Auger Electron Production

This technique is sensitive to surface structure. For comparison with Angle resolved XPS results, a Ni(100) sample has been introduced for study.

(R. Armstrong)

(f) Scattering of He Atoms from Surfaces

Light atoms, such as He atoms in the energy range 8-60 meV, provide a useful tool when scattered from surfaces (under clean conditions) for probing the outer layer of a surface or surfaces covered with gases or molecules. Recently, experiments have been performed using this technique (with energy analysis)

to study He scattering from a crystal of Au(111) and from various adsorbed species, e.g., Ar, Kr, Xe, CO.

The thrust of the work can be divided into elastic and inelastic experiments. The former will be mentioned first.

Atoms scatter elastically from a metal into regions of sharp peaks unless an object on the surface deflects the particle. Steps, which are well known to exist on metals, provide a large cross section to atoms and thus cause broadening of the base of the above sharp peaks, inducing an elastic incoherent component which can be resolved with an energy analyzer.

Flat terraces exist between such steps and if an immobile adsorbed particle is introduced it can also cause such deflection, which can lead to useful information on very dilute adsorbate layers. Consequently, a study of the elastic component in this broadened region of the peak can yield information on the mobility and cross section (apparent size) of the adsorbed species. Further, information as to when the adsorbate particles interact to form nuclei is also present. Clearly, if atoms migrate and spend more time in the vicinity of the steps the influence will be smaller due to shielding. In fact multiple steps (not monatomic) or kinks in steps can partially or completely "hide" the adsorbates.

In most experiments details in the elastic coherent component as a function of coverage (particularly in the region below 0.1) have led us to speculate on various processes which could be precursor mechanisms to condensation. This is information obtained very "early on" in the adsorption process. For instance, in the case of CO adsorption on Cu(100) and (110) a very large cross section (or increase in the elastic component) was observed due to isolated immobile molecules standing in the end-on position and developing a dipole moment which further enhanced the "geometrical" cross section. In contrast, for CO adsorbed on

Au(111) the cross section is much smaller, suggesting that the CO molecule is lying on its side. For the first time in our studies of various faces of the noble metals, increases in the elastic incoherent component have been observed for Au(111) even though the atoms are known to be mobile. In fact, the increases are comparable to the immobile CO, which suggests that the molecule is lying on its side and the result is not due to reduced dipole. These increases for the mobile gases at large dilution are not at all unexpected since the atoms spend time on terraces, which leads to the problem of why the increases were not noticed before despite efforts to see such effects. It is perhaps that previously steps have played a role or condensation has occurred at very low coverages. Further, the increases in the elastic incoherent component for the noble gases on Au(111) have tended to show slight maxima as a function of angle from the main (00) peak, a feature which was observed in our case several years ago with the CH_4-Cu(110) system. We are at loss to explain this phenomenon from current observations, unless very "long range ordering" exists. This latter effect is very slightly energy dependent. (A closed circuit cryogenic head was recently installed so that incident He beam energies down to 8 meV are now achievable.)

The theory of physisorbed gases on metals has predicted that He atoms should adsorb more strongly on Au as opposed to Ag and Cu. Presumably, this would be true of the other heavier inert gases. In any case the measurement of the inelastic energies of vibration of the noble gases normal to the surface are all higher in the case of Au, e.g., Ar, 3.9 → 4.1 meV; Kr, 3.3 → 3.5 meV; and Xe, 3 → 3.2 meV.

(B. Williams, B. Mason)

(g) Interactions of Atoms Near and On Surfaces with Light

Using recent discoveries of nonlinear laser light interaction in solids and gases, we are setting up the

necessary equipment to study and characterize surface interactions such as dynamic lineshifts, Doppler-free spectroscopy at surfaces and on optical waveguides. This technique may yield a new type of plasmon laser on GaAs semiconductor waveguides, ion pair-emission microscope for working junctions, E-field mapping, and waveguide mode amplifier for fibre-optics communication systems.

(R. Normandin, J.F. Young)

(h) Normal Metal Tunnelling

Anomalous superconducting tunnelling results on A15 compounds are often blamed on a contamination layer and the resulting proximity effect. However, a very sharp peak in the electronic density of states $N(\varepsilon)$ near the Fermi level can lead to similar anomalies. With B.,Mitrovic of Brock University, St. Catharines, Ontario, we have calculated the anomalies that would arise in normal state tunnelling due to such a sharp peak and found them to be similar to those observed in the superconducting case. Since normal metal tunnelling is not complicated by the proximity effect, the observation of such anomalies in both the superconducting and normal states would strongly favour the explanation in terms of sharp structure in the density of states.

(R. Leavens)

(i) Surface Structure in Multicomponent Systems

There is a collaborative project with the Institute for Materials Research of McMaster University, Hamilton, Ontario, exploring the application of secondary ion mass spectrometry (SIMS) at low primary energies to investigations of the surface structure of multicomponent systems. A question of particular interest is the relationship of surface ordering to bulk ordering in certain alloys. Alloys such as Cu_3Au and Ni_3Mn undergo well-known bulk order-disorder transitions as the temperature is raised. In the experiments, Auger

electron spectroscopy is used to monitor surface purity and composition and the relative SIMS yields for different species are determined as a function of temperature. Some interesting observations have been made of substantial yield variations in the case of Ni_3Mn. The SIMS yield changes are being examined in detail and correlations will be sought with theories of surface ordering.

(K. Vineberg, P.H. Dawson, G.W. Richardson)

(j) Ligand Field Absorption at Surfaces

The three-dimensional electronic states of such transition metals as Ni and Co may be split by adjacent atoms or ligands such as O. The resultant absorption of light is described as ligand field absorption and is often very sensitive to the transition metal - ligand coordination. When, for instance, Ni oxidizes, the "oxide" layer is thought to grow via a number of stages: first an O overlayer is formed, then islands of NiO form, and finally the islands coalesce and a more or less uniform NiO film is grown. Throughout this process - which has been the subject of intense study - the local Ni-O coordination changes, and hence the intensity and wavelength dependence of the ligand field absorption also changes.

We have sought to determine whether a sensitive optical surface probe such as ellipsometry may be used to trace the various stages in the oxidation process of Ni and Co by measuring the surface ligand field absorption. We have done so by model calculations: a model for the surface oxide was set up, the ellipsometric angles ψ and Δ were calculated as a function of film thickness, angle of incidence, and wavelength, and examined for evidence of ligand field absorption. We conclude that such absorption is indeed detectable even for very thin films (for instance, a 1-nm film of NiO on Ni), and that ellipsometric measurements should therefore provide useful information regarding the oxidation process.

In collaboration with B.R.,Hollebone of Carleton University, Ottawa, Ontario, recent evidence on the interaction of O molecules with crystalline Ni and Co has been examined, to identify as many as possible of the chemical species of the metal atoms which appear during the oxidation process. Once these species are anticipated, predicted ligand field spectra can be derived which contribute to the observable absorption coefficients in the ellipsometric spectra of the surfaces.

(J.G. Cook, G.C. Aers)

(k) Phase Formation at Thin Film Interfaces

The study of phase formation is particularly crucial to the problem of metallization schemes in thin film multilayer devices. Phase formation can be detrimental to the mechanical and electrical integrity of these systems. While major efforts have been made to study this problem, relatively little work has been done using high resolution electron diffraction and imaging techniques to identify the sequence of phase formation and the early stages of growth of these compounds. We are engaged in such a study using Al/Cu thin film couples as a model system.

We are also studying phase formation from the point of view of intentionally producing technologically important compounds from solid state interfacial reactions by rapid thermal annealing of Ti/Si couples. For example, we have found through detailed TEM studies that self aligned silicides can be produced by interfacial reactions between amorphous Si and polycrystalline Ti.

(K. Rajan, P.B. Sewell)

(l) Chemical Interdiffusion at Thin Film Interfaces

This program is applying high spatial resolution X-ray microanalysis and electron energy loss spectroscopy to study interdiffusion at metal/semiconductor interfaces. Such quantitative measurements can lead to the experimental determination of low temperature diffusion coefficients which it is essential to know for thin film device technology. Collaboration occurs with R.,Egerton and P.,Crozier of the University of Alberta, Edmonton, Alberta.

(K. Rajan, P.B. Sewell)

(m) Composition Modulated Thin Films

In conjunction with Alcan International Ltd. we are exploring some novel structures produced by sputtering techniques. The program is focussed on composition modulated, multilayer structures with unique physical and mechanical properties for important industrial applications and collaboration is with A.,Rosenfeld of Alcan International Ltd.

(K. Rajan, P.B. Sewell)

(n) Laser Induced Modification of Thin-film Interfaces

The use of laser processing of thin film multilayer systems is being studied. This work is aimed at studying the materials processing parameters of silicon and compound semiconductor metallizations. Of particular interest at present are metal/semiconductor systems. This study involves the use of a variety of techniques, including high resolution electron microscopy and Raman spectroscopy.

(K. Rajan, P.B. Sewell, J. Young, R. Normandin)

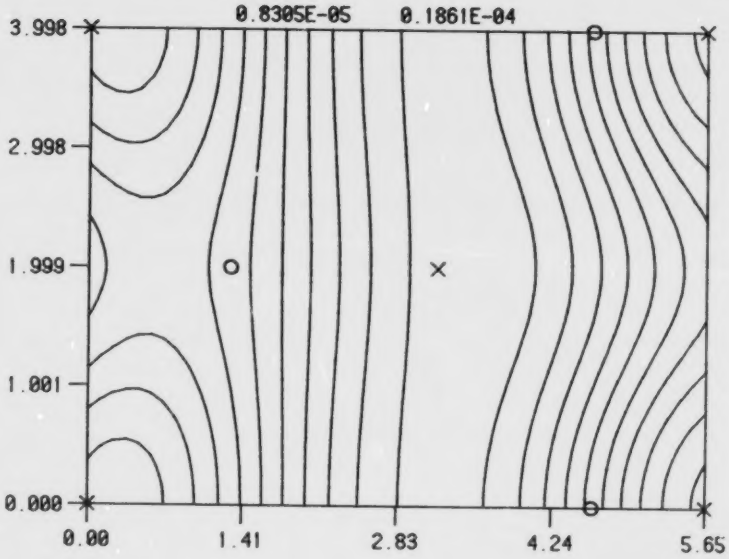

Figure 5 Atomic charge superposition contour map, 4 Å above the unit-cell of the GaAs (110) surface with projected atomic positions (x - As, o - Ga).

6. Optical Interactions with Solids

Optical properties of semiconductors are increasingly important in the communications industry as transmission by optical fibres is used. Work in the Division in this area is presented in the next two sections of this report. The optical interactions themselves are studied to increase our understanding of semiconductor physics and as a probe of the behaviour of the electrons. The section on Quantum Electronics describes the study and utilization of the optical properties. Related industrial applications are to electro-optical or all-optical devices or to optical memories.

(a) Time-resolved Raman Scattering from Non-equilibrium, Photo-generated Solid State Plasmas

The primary goal of our research in this field is to understand the fundamental interactions which dictate the natural response of non-equilibrium carrier distributions in semiconductors. A thorough knowledge of these interactions will be essential in the future development of picosecond and sub-picosecond electro-optic and all-optic devices.

We currently have an operational laboratory consisting of:

(i) a continuously modelocked YAG laser (which simultaneously pumps)
(ii) two picosecond dye lasers operating near 600 and 900 nm
(iii) a three-stage Raman spectrograph
(iv) an x-y charge coupled detector cooled to liquid nitrogen temperatures
(v) a computer control system for the detector
(vi) a liquid helium cryostat

We are presently studying the properties of coupled plasmon-longitudinal optical phonon modes in binary III-V semiconductors. For heavily doped samples the plasmon contribution is from the activated impurities,

and the associated coupled modes exist under equilibrium conditions at non-zero temperatures. The energies of the coupled modes, as determined from Raman spectra, can be used to find the concentration of activated carriers within a few thousand angstroms of the surface.

In large bandgap semi-insulating III-V semiconductors, no plasmons exist under equilibrium conditions. However, a high density plasma can be excited optically, and during its lifetime (~1 ns) coupled plasmon-phonon modes exist. By studying the properties of these "transient" modes via Raman scattering, one can study the dynamical properties of the photo-generated plasma. In particular, by spatially and temporally overlapping a 3-ps and a 70-ps pulse on the sample surface, it is possible to quantitatively follow the build-up and decay of the surface carrier concentration on a picosecond timescale. The measured temporal evolution of surface carrier concentration can then be modeled to extract the effective diffusion coefficient and surface recombination velocity of non-equilibrium carriers.

In the near future we intend to study the detailed shape of the Raman spectra from the coupled modes in order to infer the distribution function of the photo-generated plasma. Further information on the distribution function will also be obtained by Raman scattering from the single particle excitations of the plasma. Such studies will provide valuable insight into the fundamental Coulomb interactions which dominate the behaviour of non-equilibrium plasmas in semiconductors.

(J.F. Young, R. Normandin, B. Kettles)

(b) Light Scattering Spectroscopy

Light scattering spectroscopy is used to measure the dynamical properties of solids, including vibrational, electronic, and magnetic excitations. The technique is widely applied to problems in solid state physics,

including the study of the effects of disorder in solids. Knowing how impurities affect the physical properties of solids is of interest because most materials used in industrial applications are not pure. In the semiconductor industry impurities are deliberately introduced as dopants at low concentrations or to form alloys at high concentrations. Light scattering experiments on disordered solids are being carried out to provide new insights into disorder-related phenomena and to provide data with which to test theoretical models. In the past year studies have been made of the lattice vibrations and of the role of disorder in the structural phase transition in lead hydrogen phosphate and lead deuterium phosphate. Light scattering spectroscopy has also been applied to $Si/Si_{1-x}Ge_x$ strained-layer superlattices grown by the MBE Section. The vibrational spectrum of these samples contains features associated with the silicon layers and the alloy layers of the superlattice. In all of the samples studied to date, the results indicate that the Si layers are lightly strained, if at all, whereas the $Si_{1-x}Ge_x$ layers are heavily strained. Further experiments are in progress to obtain evidence for quantum-well confinement of electrons.

(D.J. Lockwood, N. Ohno, H.J. Labbé)

(c) Nonlinear Effects in Thin Liquid Crystals

A project on nanosecond light modulation and other nonlinear effects in thin liquid crystals is carried out in collaboration with the Department of Electrical Engineering of the Pennsylvania State University, University Park, Pennsylvania. Up to now, common wisdom had it that liquid crystals were very slow due to molecular reorientation times. We have demonstrated the first nanosecond light modulation, four-wave mixing, and measured acoustic dispersion to 1 gHz in thin samples of nematic PCB liquid crystal. This has obvious application in fast displays, light modulators, and the real-time correction of optical aberration in electro-optical systems for high power laser

transmission through the atmosphere. Other recent experiments and publications deal with transverse bistability, infrared to visible image conversion, and self-phase modulation in both smectic and nematic thin liquid crystals.

(R. Normandin, I.C. Khoo, Pennsylvania State)

(d) Modelling of Laser Interactions with Solids

A solution to the time-dependent thermal diffusion equation has been obtained for CW laser heating beams with intensity profiles which are either Gaussian or circularly uniform. A practical application in the field of solid-state dosimetry appears promising. We are attempting to modify the solution to account for the transient temperature rise of Ge measured in the laboratory (J. Young). The "formalism" should also prove useful in calculating the diffusion of hot-carriers in elemental semiconductors under the action of intense pulses.

A collaborative effort with P. Bräunlich (USA) and A. Epiphanov (USSR) was undertaken to assess the relative merits of avalanche ionization and multiphoton free carrier creation in the photoacoustic response of NaCl at 0.53 μm using picosecond technology.

G. Bryant of McDonnell Douglas is helping to extend the simulation code of hot-carrier dynamics in Ge to other semiconductors and other wavelengths.

(P. Kelly)

(e) Optical Properties of Sputtered Co_3O_4 Films

The optical properties of bulk Co_3O_4 specimens are known to be determined by ligand field and charge transfer absorption. Since thin sputtered films of this oxide are potentially useful for solar thermal absorption and catalysis, a study of the optical properties of Co_3O_4 films would be of interest. Furthermore, it is conceivable that the possibly high

sensitivity of ligand field absorption to the local Co-O coordination could permit optical studies to provide information regarding this coordination and the process of sputter-deposition.

We have deposited Co-oxide films by rf sputtering in an Ar/O_2 gas mixture under a wide variety of sputtering conditions and determined their optical properties by absorption spectroscopy and ellipsometry. With few exceptions, the films are intensely absorbing, and their spectra very similar to those of bulk Co_3O_4. Indeed, X-ray and electron diffraction indicate the films to be fine-grained Co_3O_4.

In a joint project with B.R. Hollebone and K. Miedzinska of Carleton University, Ottawa, Ontario, the theory of ligand field absorption by Co_3O_4 has been examined in some detail. Published assignments have been found to be incorrect, in that the absorption of photons by the Co^{2+} and Co^{3+} ions in the spinel Co_3O_4 lattice are assumed to be independent processes. Instead, the absorption must be considered to be the interaction of a photon with the complete unit cell. This interaction has been considered in some detail, and new assignments have been made to the observed absorption peaks. The absorption is not Laporte-forbidden, but allowed and intense, in agreement with experiment.

When Co is reactively co-sputtered with some Ni, the absorption is observed to be even more intense, but the peaks are less prominent. This is due to the formation of Ni^{2+} and Co^{3+} ions and the onset of charge-transfer absorption. Furthermore, the Ni 3D electrons interfere with the electronic structure of Co_3O_4.

(J.G. Cook, M.P. van der Meer, G.C. Aers)

(f) Optical Properties of Sputtered NiO Films

Ni oxide films have been laid down by reactive sputtering of Ni in Ar/O_2 mixtures. X-ray diffraction indicates the films to be NiO, but they are much more intensely absorbing than bulk NiO: their extinction coefficient k ($\tilde{n} = n - ik$) for visible radiation is

near 0.5, two orders of magnitude above that of bulk NiO. The spectra contain little structure. The absorption is not sensitive to the oxygen flow rate during deposition once a critical rate has been exceeded, but is quite sensitive to the total gas pressure and to the substrate temperature. When the films are heated past 400°C they give off oxygen and become less black. Most if not all of these effects may tentatively be ascribed to impact implantation of oxygen atoms into the NiO lattice during the sputtering process, which produces Ni^{3+} ions, thus giving rise to intense charge transfer absorption between Ni^{2+} and Ni^{3+} atoms. These effects have not previously been observed in NiO films.

(J.G. Cook, M.P. van der Meer, G.C. Aers)

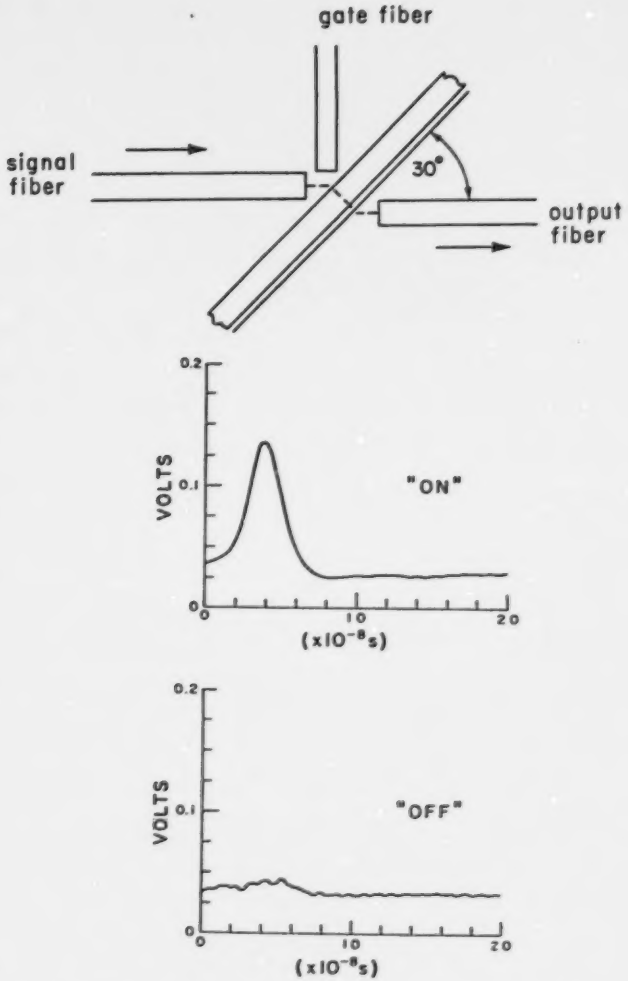

Figure 6 Fast fiber optic switch: A 60 μm thick silicon wafer, tilted at Brewster angle, transmits light from the signal fiber to the output fiber. When light is present on the gate fiber (~4 μJ) the induced defocussing by the refractive index gradient destroys the fiber-fiber coupling.

7. Quantum Electronics

(a) Channel Waveguide for External Modulation in Fibre Optical Communication Systems

This project, in collaboration with BNR, is to explore one aspect of multi-gigahertz fibre optical communication. Although good results are obtained by directly modulating the laser source it might be better to have a stable, single mode, high power laser as the light source and externally modulate the light. We have built several mode extinction channel waveguide modulators in $LiNbO_3$ with simple, direct write lithography using a fast atom bombardment (FAB) system to deposit a titanium line on the y-cut $LiNbO_3$ substrate. Gold electrodes were then deposited over the channel to modulate its refractive index to cut off the waveguide. Modulation speeds over 1 GHz were measured (limited by our instrumentation). Measurements at higher speeds are presently being done at BNR to reach the limit of the transfer curve of the modulator.

(R. Normandin, V. So, P. Vella)

(b) All Optical and Electro-optical Logic in Fibre Optics

In the near future it seems clear that electro-optical data processing will dominate over conventional VLSI electronics in ultrafast systems and supercomputers (i.e., GaAs-based electronics where optical interconnections are seen as the only way to move signals around a VLSI circuit fast enough and also as interboard connection for supercomputers). However, intrinsic or all-optical processing will eventually take over. There is already much research in areas such as Fabry-Perot multiple quantum well (MQW) bistable devices, interferometry, and Kerr effect gates for performing logical decisions at femtosecond speeds. We recently demonstrated an ultrafast device in fibre optics using induced defocussing as a gate and a binary adder. This new class of devices is very simple

and stable and operates at low optical powers, compatible with present AlGaAs fibre communication systems. Improved performance with MQW structures will hopefully be demonstrated in the coming months. We are building a mode locked Nd YAG laser to generate 16-ps pulses to further demonstrate the device potential in ultrafast logic systems.

(R. Normandin)

(c) Ultrafast Streak Camera in an Integrated Optics Context

An applied project deals with the fabrication of an ultrafast streak camera for accurate picosecond timing of light pulses in fibre optical systems. The scanning is provided by an electro-optical birefringent prism on a titanium diffused waveguide fabricated with an ion beam deposition system. A liquid-nitrogen-cooled CCD detector is used to integrate the signals of interest and provide a display. This system will see applications in optical radars, multiplexing for fibre optics communication systems, and nonlinear optics diagnostics. We are now waiting for MBE grown GaAs films to proceed further.

(R. Normandin, B. Kettles)

(d) Surface Plasmons and Nonlinear Optical Response

The feasibility of using surface plasmons to obtain a nonlinear optical response that could be used as the basis of an all-optical device is being investigated. Surface plasmons are attractive candidates for nonlinear devices because they provide field enhancement which reduces the input intensity required to obtain a nonlinear response. They also have a narrow resonant width so that relatively small changes of the index of refraction are required to nonlinearly change the properties of the device. The nonlinear interaction of surface plasmons at a silver/organic solvent interface has been demonstrated both with continuous and

pulsed (nanosecond) radiation sources. The responses observed to date are due to a thermally induced change in the refractive index of the solvent brought about by energy absorbed by the metal from the surface plasmon. Although this limits the response time of the device to a few milliseconds, nanosecond switching of a continuous-beam helium neon laser by a 20-ns-long laser pulse can be achieved by using a suitable geometry. The basic principle already demonstrated will be applied to a solid/metal interface using picosecond laser pulses when the facilities for producing the samples and generating the picosecond pulses become available.

(J.F. Young, R. Normandin)

(e) Two Pulse Photon Echoes

Echo modulation studies of three of the four ground spin levels of the R_2 line in ruby have been completed and a paper has been accepted for publication. Theory predicts that the fourth level can be seen only at large magnetic fields (>10,kg) with the current system time resolution, which is fundamentally limited by the dye laser power output. The purchase of a superconducting magnetic system to test this prediction and the cross-prelaxation model described earlier[1] is being considered.

The main result is that excellent agreement between theory and experiment was obtained for the spin -1/2 and -3/2 levels. Extension of the existing theory was necessary to account, with fair success, for the +1/2 level modulation, in particular inclusion of nuclear polarization and finite linewidth effects. Further computations are needed to distinguish between the two possibilities.

(A. Szabo)

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[1]DMS Activities 1984.

(f) Three Pulse Echoes

The three pulse or stimulated echo has long been studied at rf (NMR) and microwave (EPR) frequencies. However, no detailed experiments have yet been reported for optical transitions. In addition to the scientific interest, such studies are important for hole-burning optical memories since the stimulated echo measures how the hole diffuses in frequency space. This diffusion ultimately limits, together with the homogeneous linewidth, the number of colours which may be stored in one physical location.

A detailed series of measurements on the spin-1/2 level has been completed. A surprising result is that the decay occurs in three stages. Calculations are underway to fit the data to the Hu-Hartmann[1] uncorrelated sudden-jump diffusion model as well as the Klauder-Anderson[2] and Mims[3] Gauss-Markoffion models. Two of the (fast) decay regions seem straightforward and are consistent with Cr-Cr and Al-Al spin-flip induced spectral diffusion. The remaining decay component appears to be a mixture of population decay and slow diffusion. The source of the slow diffusion is still a mystery. Analysis of the data continues.

(A. Szabo)

(g) Dye Laser Frequency Stabilization

A phase modulator and fast servo electronics have been assembled for dye laser stabilization. A conventional Hall type stabilizer built here earlier achieved a linewidth of ~10 kHz. However, it was limited by a short locking period. The present system uses FM modulation and homodyne detection of the error signal and is expected to produce long-term widths <1 kHz.

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[1] P. Hu and S.R. Hartmann, Phys. Rev. B9, 1 (1974).
[2] J.R. Klauder and P.W. Anderson, Phys. Rev. 125, 912 (1962).
[3] W.B. Mims, Phys. Rev. 168, 370 (1968).

Such a laser will allow high resolution frequency domain studies and improvements of the time domain (photon echo) studies.

(A. Szabo)

(h) Hyperfine Structure of Rare Earth Ions in Optical Solids

The rare earth ions possess highly resolved optical spectra because the responsible electrons are isolated from their environment by closed shells of electrons. Using laser spectroscopy one is able to measure small interactions such as those which are present because the nucleus of the rare earth ion has a spin I. This interaction is known as the hyperfine interaction. For half integral spin, it produces I + 1/2 levels, separated by a tens megahertz for each electronic level. While the state-of-the-art dye laser spectroscopy resolves a few kilohertz, it is somewhat simpler to use double resonance techniques where a radio frequency magnetic field is used together with a narrow-band dye laser (0.2 MHz FWHM) to examine this hyperfine structure. Several years ago, with K.K. Sharma, we succeeded in measuring for the first time, the hyperfine interaction in trivalent Eu^{3+}. The dominant contributions to the interaction are the electric field gradients produced by the lattice charges and the six equivalent 4f electrons. It is of interest to determine the magnitudes of each of these interactions in order to "measure" certain atomic constants. One method was reported last year,[1] where the same state in two different host crystals was measured and which clearly demonstrated the strong host dependence of the hyperfine interaction. However, because the lattice constants differ for the two hosts, the analysis is difficult, so a second method was investigated in this period, where the hyperfine interaction was measured in two electronic states in one host crystal. The

[1] K.K. Sharma and L.E. Erickson, J. Phys. C, in press.

data from the previous measurement[1] were combined with a new measurement of the $^5D_0$ excited state to allow a separation of the two components using a model given by Barnes et al.[2] The predicted ratio[1] of the two interactions (-2.9) obtained from the best known values of several atomic constants was found to be higher than the experimental value (-2). Some uncertainty remains, largely connected to the uncertainty of the directions of the principal axes of the two interactions.

(L.E. Erickson)

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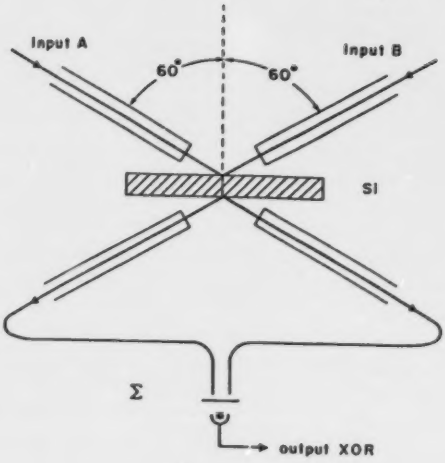
[1] L.E. Erickson and K.K. Sharma, Phys. Rev. B24, 3697 (1981).

[2] R.G. Barnes, R.L. Mossbauer, E. Kankeleit, and J.M. Poindexter, Phys. Rev. 136, A175 (1964).



XOR

A	B	OUT
0	0	0
0	1	1
1	0	1
1	1	0

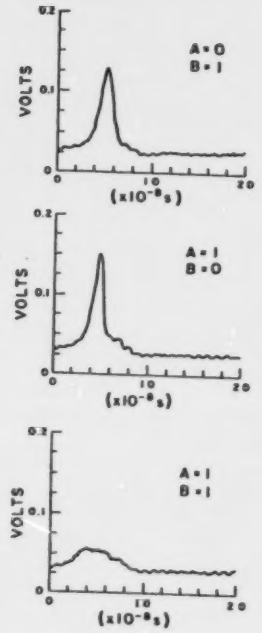


Figure 7 Fiber optic "XOR" logic gate: The 60 μm thick silicon wafer can transmit light when either input A or input B carries light but not when both are. Induced defocussing then reduces the output coupling so that little light is transmitted, thus performing the operation of an exclusive OR gate. Films are ~8 μm in diameter.

8. Coherent States of Electrons

(a) Critical Magnetic Field, Proximity, and Josephson Effects in Heavy-Fermion Superconductors

Recently, superconducting metals have been discovered in which the inertial mass of the electrons is about 200 times the usual electron mass, $m^* \approx 200\ m_e$. Two major questions occur, for which at present no-one has the answers: (i) what causes the heavy mass; and (ii) what causes the superconductivity?

Such heavy electrons should experience much larger (less screened) Coulomb mutual repulsion, and it is difficult to see how the usual state of electron pairs could occur in which the pair orbital state is isotropic, with even parity. In this situation lattice-distortion or virtual phonon effects should not produce an electron-electron attraction sufficiently strong to overcome the Coulomb repulsion so that the necessary pairs could form. However, if the quantum wave function of the electron pair is anisotropic odd parity, necessarily with spin S = 1 or triplet, then pairing can occur even with a net-repulsive electron-electron interaction. The reason for this is that nearly backward scattering of electrons by electrons (short-range scattering) effectively multiplies the electron-electron interaction by a change of sign of the pair wave function. If the forward (long-range) scattering is sufficiently weakly repulsive in comparison, or attractive, a bound electron-electron pair can occur.

One of the major thrusts of condensed matter theory in the past year has been toward describing heavy-Fermion superconductivity as a condensed state of anisotropic, odd-parity, triplet-spin Cooper pairs. A significant complication in this is that for the superconductors UBe_{13}, $CeCu_2Si_2$, and UPt_3, strong relativistic effects occur so that orbital and spin character are thoroughly mixed, known as strong spin-orbit coupling. We have developed theories for critical magnetic fields,

proximity, and Josephson effects. These theories in conjunction with experiments this year, including Josephson vacuum tunnelling experiments at Jülich, suggest strongly that $CeCu_2Si_2$ is not a triplet superconductor as expected, but instead is an even-parity, but probably anisotropic, superconductor. In this case electron pairs would still involve electrons not close to each other, taking advantage of some attractive interaction at long distances but avoiding Coulomb repulsion at short distances. (This repulsion is of the form where two electrons on the same lattice site strongly repel each other.) No picture even this clear has emerged for UBe_{13} and UPt_3.

(E.W. Fenton, G.C. Aers)

(b) Magnetic Superconductors

We have determined the lowest-energy state of a superconductor in the presence of antiferromagnetism which has wavelength twice the period of the host lattice. In a series of papers, we have shown that Cooper pairing in the lowest-energy state is charge-isotropic but spin-anisotropic, just like the normal metal state of the antiferromagnet at higher temperatures. This contrasts with two competing pairing schemes developed in 50 or 100 papers over the past 23 years wherein the Cooper pair state is either spin-isotropic, unlike the normal state, or charge-anisotropic, also unlike the normal state. The new Cooper pairing state has lowest energy because the superconductivity in the presence of antiferromagnetism does not change the charge or spin symmetry of the metal, just as would occur for usual superconductors. We have determined the major physical properties arising from this pairing scheme, which in fact mixes spin-singlet and spin-triplet pairs. This pairing state responds to any charge-isotropic interaction, e.g., an isotropic electron-electron interaction or scattering by non-magnetic impurities, just like isotropic s-wave pairing in a nonmagnetic metal.

(E.W. Fenton)

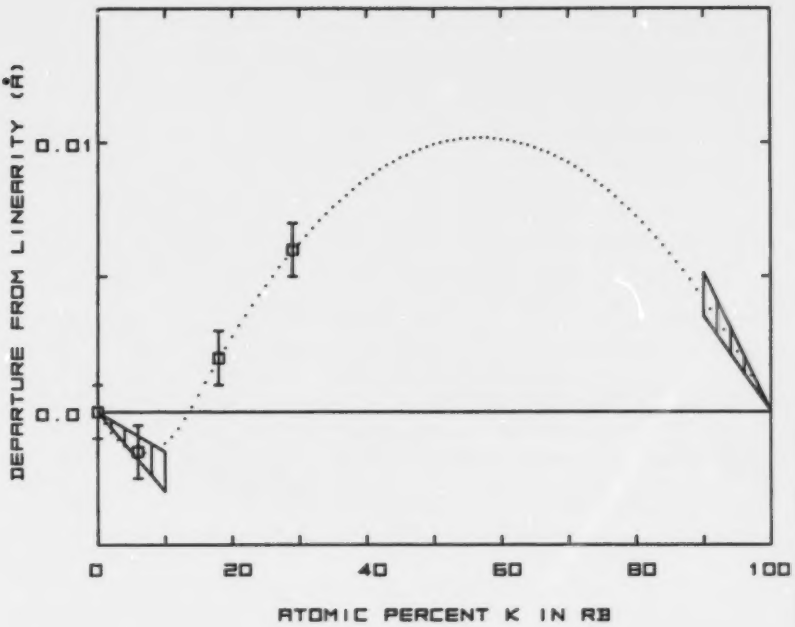


Figure 8 Departure from linearity of lattice constant with concentration over the Rb-K alloy system. The points are taken from the neutron diffraction measurements of Kamitakahara and Copley, assuming a value of 5.327 Å for K at room temperature, and the dotted line is a smoothly joined pair of parabolas through these points. The differences between our measured initial slopes and a linear interpolation are indicated by the shaded segments which show the (extrapolated) uncertainty range for our measurements at each end of the system.

9. Electronic Structure

(a) Heavy Fermion Systems

Only three heavy Fermion materials are superconducting: $CeCu_2Si_2$, UBe_{13} and UPt_3. $CeCu_6$ is interesting because it is commonly believed to be almost superconducting and good single crystals can be grown. It is therefore a good candidate for observing de Haas - van Alphen (dHvA) signals. Crystals of the homotype $LaCu_6$ have shown signals but in $CeCu_6$ no signals were observed at 1 K and 10 T. Attempts will be made at 30 mK and 15 T at the University of Sussex when their system is operating again early in 1986.

In the process of characterizing samples the resistivity and magnetoresistivity have been measured down to 20 mK. A T^2 dependence, with a large anisotropic coefficient was found at the lowest temperatures, and a negative magnetoresistance with a very complicated temperature dependence has been observed. Although not yet understood this is presumably related to the condensation into the coherent state.

(P.T. Coleridge)

(b) Exchange Enhanced Paramagnets

The susceptibility of pure Pd is enhanced about 10 times by exchange effects, and the addition of small quantities of Ni or Fe induces ferromagnetism. Microscope details of the exchange enhancement and the onset of ferromagnetism are obtained from the de Haas - van Alphen effect. In collaboration with Professor Springford's group at the University of Sussex these effects have been studied for electrons on the X-central ellipsoids in Pd. In pure Pd the anisotropy of the exchange splitting is dominated by spin-orbit effects. In the paramagnetic alloys the extra exchange interaction was determined to be ferromagnetic and anisotropic over the Fermi surface. In Pd(Fe) ferromagnetism probably arises from coupling of the

"giant moments" formed around each impurity atom; in Pd(Ni) the results suggest that Pd(Ni) is a spatially homogeneous system with a uniformly enhanced exchange splitting of the conduction band electrons. The results emphasize the relationship between spin fluctuations and the onset of ferromagnetism.

(P.T. Coleridge)

(c) Dilute Copper Based Alloys

These alloys provide a well-understood group of alloy systems to study the interaction between conduction electrons and impurities. A paper was published showing that for typical heterovalent, homovalent, and transition metal impurities the impurity resistivity can be calculated in closed form from scattering rates. When experimentally determined scattering rates are used there is good agreement with experiment but the commonly used "free electron" or spherical band model was wrong by up to 50%.

(P.T. Coleridge)

(d) de Haas - van Alphen Effect in Alkali Metal Alloys

Many electrical and magnetic properties of metals and alloys depend on details of the energy relationship between conduction electrons and the crystal lattice, that is, upon the electronic structure. One of the most powerful experimental tools for studying the electronic structure is the de Haas - van Alphen (dHvA) effect, which measures properties of the Fermi surface (FS). We have developed some unique high-precision techniques in this field which have been used in a number of recent studies. The experiments generally require a small (1 mm × 1 mm × 3 mm) rather perfect single crystal of the pure metal or alloy concerned. The sample is placed in a high, very uniform magnetic field (<8 T) at low temperatures (~1 K). It may be tilted, rotated, or subjected to hydrostatic (liquid helium) pressure. We study the oscillatory

diamagnetism (dHvA effect) using a high-sensitivity, low-noise AC bridge in fields which can be measured with a relative precision of 1 part in 10^6.

The alkalis are nominally the "simplest" metals electronically and are therefore ideal vehicles for the study of some fundamental aspects of the electronic structure of metals. Their extreme reactivity makes them difficult to handle, but we have developed appropriate techniques to allow the preparation in a helium glove-box of single crystal specimens suitable for dHvA measurements, and their transfer to a cryostat without damage or exposure to the atmosphere.

Current studies, now essentially complete, are concerned with the effect of alloying at the 1,at.% level. This is the maximum amount of one alkali which can be alloyed into another without increasing the conduction-electron scattering to the point where dHvA signals can no longer be observed. The alkalis are ideally suited for an investigation of the effect of the distortion in a formerly uniform lattice resulting from the addition of solute atoms of a different size. These studies have allowed us to confirm the assumption that the lattice-constant determined by X-rays, etc., is that appropriate to the dHvA effect. They will also allow the testing of theoretical models of dilute homovalent alloys and an appreciation of the success or failure, in the non-uniform environment of an alloy, of mathematical treatments developed for the uniform conditions of a pure metal.

A paper was published on the K-Rb system. Studies in the Rb-Cs system, where the FS is appreciably more distorted, have been completed.

(I.M. Templeton)

(e) Correlations in the Electron Gas

We are collaborating with D.,Neilson and co-workers at the University of New South Wales, Sydney, Australia,

to understand the importance of correlations in the dynamic structure factor, $S(k, \omega)$, of the three-dimensional electron gas. A fairly simple model of the exchange contributions to $S(k, \omega)$ combined with the Neilson et al. correlation calculations have provided a satisfactory fit to experimental measurements of $S(k, \omega)$ for electrons in solid Al and Li. In trying to extend these results to make predictions for Na, K, and Rb (lower electron densities) we have found that certain sum rules were no longer approximately satisfied. We are currently trying to rectify that problem.

(R. Taylor, M.W.C. Dharma-wardana)

(f) Electric Microfields

The fluctuating electric field felt by a test charge placed in a medium containing mobile carriers is called the electric microfield. This is of importance in the theory of impurity spectra, etc., and we have continued the previous research on this topic where we have developed new methods based on density functional theory and classical statistical mechanics.

(M.W.C. Dharma-wardana, in collaboration with
F. Perrot of the French Atomic Energy Commission)

(g) Self-consistent Calculation of the Response Function for a Non-equilibrium Distribution of Electrons

With sub-picosecond laser pulses it is possible to excite a nearly mono-energetic distribution of electrons in the conduction band of semiconductors. The manner in which this distribution approaches a quasi-equilibrium state is of current interest to many researchers in the field. Most models developed to treat such photo-generated distributions have only included the Couloumb interaction in a phenomenological manner. To make further progress, we have done a self-consistent calculation (within the RPA) of the real and imaginary parts of the dielectric response

function of a nearly mono-energetic distribution of electrons. The self energy of various states within the conduction band, in the presence of the photo-generated distribution, was also calculated and used to infer the lifetime of these states. Preliminary results appear to be in good agreement with recent experiments.

(J.F. Young)

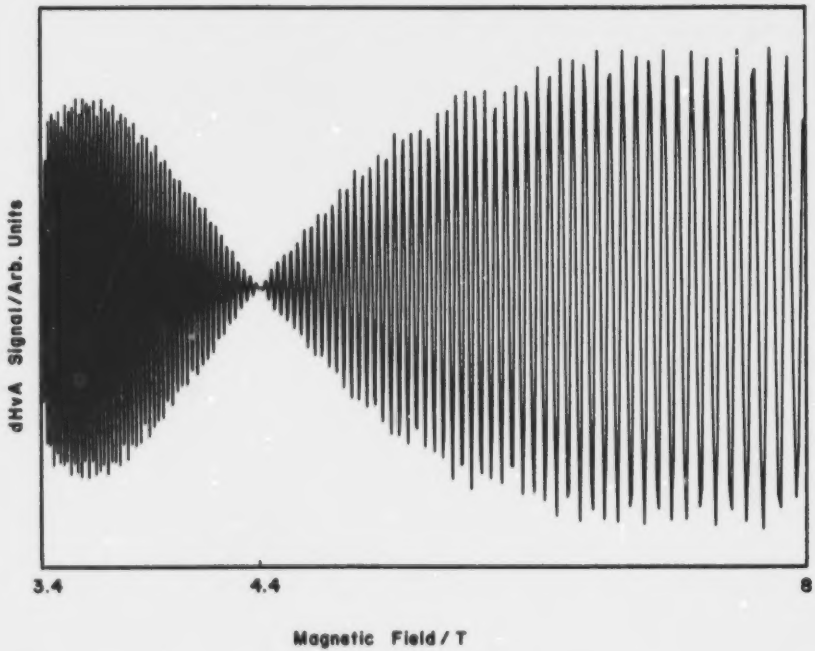


Figure 9 "Spin-zero" in de Haas - van Alphen oscillations from Pd(Fe) induced by the exchange interaction between the conduction electrons and localised Fe moments.

10. Microscopic Structure

(a) Interatomic Potentials

A recent development in the technique of Molecular Dynamics (MD) computer simulation has been the Parinello and Rahman procedure for allowing the MD cell to change shape during the simulation run. This allows the possibility of studying thermodynamic properties, phase diagrams, and nucleation effects with realistic boundary conditions on the cell. In collaboration with A.B. Walker at the University of East Anglia we are developing the necessary formalism to incorporate properly all metallic density-dependent effects in the Parinello-Rahman procedure. We then hope to use the procedure to study phase diagrams of several simple metals. We are also planning to set up another collaboration with J. Ray at Clemson University, Clemson, South Carolina, and A. Rahman at the University of Minnesota, Minneapolis, Minnesota, to do a thorough simulation of thermodynamic properties and also nucleation effects in alkali metals and mixtures of alkali metals.

In addition to the foregoing, work is continuing on the review article and books on interatomic potentials in metals described in the previous report.

(R. Taylor)

(b) Structure of Liquid Semiconductors

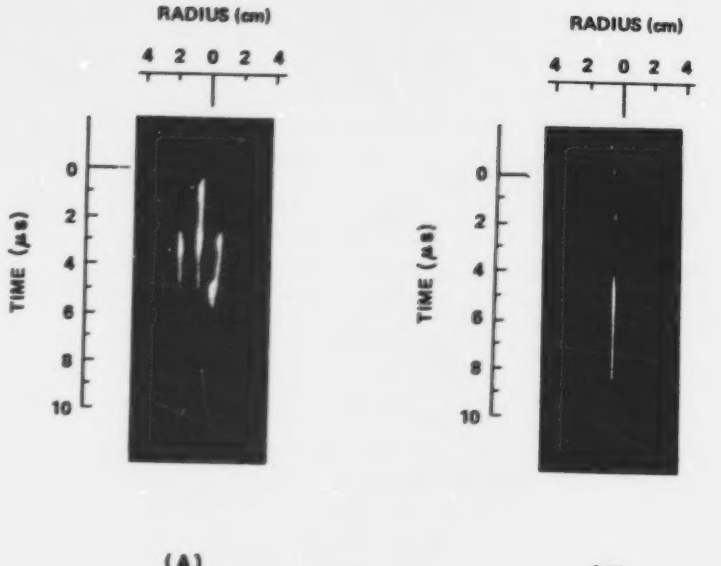
The properties of molten Ge and Si are of importance in technology but our theoretical understanding of these elements is still very poor. In particular, the structure factors show peculiar shoulder features which have not had a clear explanation. We have analyzed the experimental structure factor using pseudopotential theory and the modified-hypernetted-chain equation and presented a consistent explanation of the structure of these fluids.

(M.W.C. Dharma-wardana, G.C. Aers)

(c) Structure of Liquid Transition Metals

The well-known difficulty with d-electron interactions in transition metals has prevented any attempts to analyze the structure of these liquids. We have developed a model interaction wherein we calculate the structure of the fluid and the phonon spectrum of the solid in an attempt to explain the observed features in a consistent manner. The method has been applied to liquid Fe with moderate success. Further work is in progress.

(M.W.C. Dharma-wardana, G.C. Aers, R. Taylor)



(A) (B)

Figure 10 (A) Streak record of plasma luminosity which shows the imploding shock waves compressing the central plasma. (B) The central plasma as observed through a narrow band interference filter centered at λ = 3990 Å. (Gas, hydrogen; Pressure, 116 psi = 8 atm = 6000 Torr; Density, 2.14×10^{20} cm^{-3}; Condenser bank energy, peripheral discharges ~1 kJ, central discharges ~30 J; Containment time, ~2 μs; $n\tau \approx 4.27 \times 10^{14}$ cm^{-3} s.)

11. Other Topics

(a) Calorimetry

Calorimetry is an old but powerful technique for investigating properties of matter. Any temperature-dependent repopulation of energy levels is reflected in the specific heat. Thus the total measured specific heat may be a summation of contributions from a number of different physical processes but the form of some or all of the contributions may be known and the individual effects may be separable, especially when accurate measurements over a wide temperature range are available. The laboratory has four different sets of apparatus operated under computer control and covering the temperature range from 0.35 to 470 K.

Work has continued on the spin-glass problem. Spin-glasses are dilute magnetic systems where the ground state corresponds to an apparently random orientation of spins. The study of these systems has raised several questions, such as "is the spin glass state a new phase of matter?" They may also provide models for learning and memory in biological systems. As described in last year's report, small effects seen in the specific heat lend support to the existence of a phase transition between the paramagnetic and spin-glass states. Two papers on Cu-Mn were written and published during the year and experimental work was restarted on the Au-Fe system.

A new calorimeter covering the 15 to 320 K range was brought into use during the year. A novel feature for this temperature range is that thermal contact with the sample is made via a grease film, rather than by exchange gas, making for easier sample changing. The apparatus shows great promise with a precision of the order 0.01% in specific heat. The noble metals copper, silver, and gold have been measured. Copper is of interest in connection with its use as a calorimetric standard sample. There are no other modern measurements on silver and gold. In collaboration

with J.,Ancsin (Heat and Thermometry Section, Division of Physics), a water triple point cell was developed which would fit in the calorimeter (in place of a sample) to facilitate high accuracy thermometer calibration checks.

(D.L. Martin)

(b) Quadrupole Mass Spectrometry

A small effort is maintained on the design and applications of quadrupole mass spectrometers. Quadrupoles account for over 80% of all mass spectrometer systems sold. The principal applications are in systems for (i) organic, (ii) elemental, and (iii) residual gas analysis, e.g., in semiconductor processing.

(i) A product of earlier work was the joint development with Sciex Inc. of Thornhill of a triple quadrupole (MS/MS) system. This was carried out under the NRC Program for Industry/Laboratory Projects (PILP). The instrument was designed for unambiguous analysis of trace impurities in air, water, soil, foodstuffs, etc. It is being successfully marketed by the company, particularly in the mobile version and in a cargo examination system. Consulting is provided to the company concerning its on-going improvements and in the possible development of compact, lightweight (e.g., military) systems. Our work on the fundamental aspects of collision-induced dissociation has been completed. The alternative of collision-induced dissociation by collision with a solid target is being investigated.

(ii) Sciex Inc. have also developed a system for trace element analysis by ICP/MS (inductively-coupled plasma mass spectrometer) for which we have provided advice on the quadrupole design aspects.

(iii) Quadrupoles have some design limitations as residual gas analyzers despite their widespread

use. We have a small effort - including design theory and experiment - examining the limitations and looking at new modes of operation. A novel way of operating the quadrupole in the rf-only method of operation has been developed and a patent application has been filed. (Already we hold one basic patent on rf-only operation.)

(P.H. Dawson, G.W. Richardson)

(c) The Spherical Pinch as a Neutron Generator

Work on the development of the Spherical Pinch machine into a powerful neutron generator for material studies has proceeded in the past year, and two essential results for a copious generation of neutrons have been achieved. Firstly, the plasma in the center of the spherical vessel has reached, albeit for a very short time of the order of a few nanoseconds, a temperature of about 2,keV, as derived from a measurement of the velocity of the diverging shock wave. Secondly, the imploding shock waves created at the periphery of the vessel at several atmospheres of initial pressure are capable of containing the central plasma for a few microseconds and with a high degree of stability. (Page 65 shows such a plasma as detected with an image converter streak camera.) Work is now underway to synchronize the two phenomena, namely to contain and compress with the imploding shock waves the central plasma when this is at its state of maximum temperature. At the same time, a numerical simulation of the entire set of events is being set up to optimize the parameters of the phenomenon.

The interest in the machine by Ontario Hydro through the Canadian Fusion Fuels Technology Project has continued to be expressed and a full cost estimate to develop the Spherical Pinch into a neutron generator competitive with the Rotating Target Neutron Source has been requested and will be submitted shortly.

(E. Panarella, V. Guty)

(d) Resolidification of Cadmium in Space

The experiment was flown, a year later than planned, on 26 November - 3 December 1985 on board the space shuttle Atlantis. This was Atlantis' second flight (61B) and the 23rd shuttle flight. The experiment was included in a Getaway Special (GAS) kindly provided by Telesat Canada, which also contained a mirror-making experiment from two students from Charlebois High School, Ottawa, Ontario.

Preliminary examination of the apparatus and specimens has shown that, although successful results were obtained, the experiment did not proceed as planned. In particular, the fuse in the "crowbar" circuit was intact, indicating that the power was on for the full allowance 10 min 40 s, rather than approximately 8 min as on earth. This in turn indicated that the temperature registered by the controlling thermocouple did not reach its cutoff temperature. It is thought that the heat transfer in space was less efficient than on earth, probably because there is no gaseous convection; this change was not properly taken into account in the experimental design. Two of the 10 specimens showed shiny surfaces, indicative of melting, as far back as the close-fitting section of the container, as planned. Both were in containers with indentations near the base which presumably aided the heat transfer. Four specimens showed shiny surfaces about 1-2.5 cm along the free standing section. The final two specimens, both in 10 cm tubing rather than 6 cm, did not melt at all. Of the specimens which melted none grew in the tear drop or spherical shape expected. Instead they retained a basically cylindrical shape. Two possible causes are that the cadmium only melted in a surface layer, or than an unmelted oxide skin acted as a container in the microgravity environment.

Special containers have been made which will allow the specimens to be kept in an inert atmosphere after the original containers have been opened. Examinations planned include optical microscopy and photography,

X-ray and electron microscope examinations, etching, and sectioning.

(F.R. Lipsett)

(e) Metal Single Crystal Preparation

"Heavy Fermion" compounds, based on Ce or U, are of considerable current interest. Single crystals of $CeCu_6$ and its homotype $LaCu_6$ have been grown by the Czochralski method. The residual resistivity of the $CeCu_6$ (measured at 20 mK) was of order 1 μΩ cm which is at least five times less than the best achieved by other groups. Success was achieved by replacing the Ta crucibles by tungsten and by passivating the metal at all stages in the process. The problem of lead attachment was overcome by a copper plating process.

(R. Boulet, D. Ravot, P.T. Coleridge)

Attempts are being made to grow a large homogeneous single crystal of $Cu_{99}Mn$ for calorimetric measurement.

(R. Boulet)

(f) Purification of Rubidium

The lack of sufficiently pure rubidium (Rb) metal on the commercial market was hampering the continuation of some alkali metal studies. Material of nominal 99.9% purity is often found to contain considerably more than 0.1% impurity, such that the low-temperature resistivity of (supposedly) equally pure Rb from different suppliers can vary by more than a factor of 10. Zone-refining appeared to offer some prospect of improvement in quality, but trials of this method of purification were unsuccessful. More than 100 passes of a 1-cm molten zone along a 20-cm length of Rb under dry oil produced no detectable difference in resistivity between the two ends. However, careful fractional distillation in quartz under vacuum, rejecting the

first one-quarter to one-third of the distillate (which presumably contains the dominent impurity, cesium) gave a 2-3× reduction in the low-temperature resistivity. This material, although not ideal (RRR ~ 300), was sufficiently pure for our experiments.

(I.M. Templeton)

C. COLLABORATIONS WITH INDUSTRY

The Division encourages interactions with Canadian industry and is building up the kind of close collaborations that lead to technology transfer. The interactions range from consultations to extensive use of the Division's facilities and personnel. Some of the major in-house collaborations are listed below.

The Si group of the MBE Section had the first nine collaborations which follow:

(i) Ga-As MBE growth on Ge/Ge-Si/Si MBE <100> substrates. T. Springthorpe, Bell Northern Research (BNR).

(ii) Si-Ge strained layer superlattices, as 1.3 and 1.55 μm photodetectors. M. Gallant, BNR.

(iii) Solid phase epitaxial regrowth of Ge grown through SiO_2 masks on Si by MBE for P channel MOS devices. T. McKelwee, Northern Telecom (NT).

(iv) Ge on SiO_2 by MBE for SOI applications. T. McKelwee and I. Calder, NT.

(v) An AES, SEM, TEM, and SIMS study of Si <100> surfaces for MBE growth. F.R. Shepherd and J. Cook, BNR.

(vi) X-ray topography, cathodoluminescence and double crystal X-ray diffraction studies of Si-Ge strained layer superlattices (NATO grant in process). G. Brown, Royal Signals and Radar Establishment, and G.L. Malvern, Worcestershire, U.K.

(vii) Fabrication of a monolithic hot electron transistor by Si MBE. J. Harris and J. Shannon, Philips Research Labs, Redhill, Surrey, U.K.

(viii) RBS and ion channeling studies of Si and Si-Ge superlattices grown by MBE. T. Jackman, AECL, Chalk River, Ontario.

(ix) Characterization of Pb-Ge sputtered films by RBS, EMMA, SEM, and STEM EDX. G. Carpenter and R. - Packwood. PMRL, CANMET, Energy, Mines and Resources, Ottawa, Ontario.

(x) The GaAs group of the MBE Section had a collaboration on the growth and characterization of GaInAs films with T. Springthorpe and C. Miner, BNR.

(xi) T. Springthorpe of Bell Northern Research has provided a GaAs/GaAlAs heterostructure for evaluation by M. D'Iorio of the magnetotransport properties at very low temperature.

(xii) J.J. Harris of Philips Research Laboratory has spent a month with M. D'Iorio to initiate a research project on electric field and hot electron effects on GaAs/GaAlAs heterostructures.

(xiii) J. Furneaux of the Naval Research Laboratory is working in collaboration with M. D'Iorio on the effect of interface charges in Si-MOSFET transistors on the quantization of the Hall resistance.

(xiv) E. Mendez of IBM (Yorktown Heights) is collaborating with M. D'Iorio on the study of transport properties of 2D holes in GaAs/GaAlAs heterostructures at very low temperature and high magnetic field.

(xv) P.H. Dawson is collaborating with Sciex Inc. on quadrupole technology.

(xvi) M. Simard-Normandin of Northern Telecom has an ongoing program with R. Normandin using the dual wavelength ellipsometer for implanted silicon wafer evaluation.

(xvii) Ultrafast $LiNbO_3$ channel waveguides for V. So and P.J. Vella of Bell Northern Research were fabricated using a novel direct-write technique with a Fast Atom Bombardment (FAB) system developed by R. Normandin.

(xviii) There exists a continuing collaboration between J. Young and M. Simard-Normandin of Northern Telecom, directed towards further characterization of ion-implanted silicon using the infrared total reflection system which was developed at NRC.

(xix) J. Young continues to collaborate with M. Gallant of Bell Northern Research on a variety of projects of mutual interest. We are currently using Raman scattering to infer the near surface activation of Zn in InP.

(xx) T. Springthorpe of Bell Northern Research has grown AlAs/GaAs multilayer structures for use in J. Young's picosecond Raman scattering experiments and we hope to be able to provide feedback through our results.

(xxi) G.C. Aers has been consulted by J. Glinski of BNR on problems related to zinc diffusion into semiconductor surfaces.

(xxii) S. Dzioba of BNR is collaborating with D.J. Lockwood on investigations using light scattering to examine dielectric coatings on semiconductors.

(xxiii) D. Dautovitch of Ontario Hydro with E. Panarella to develop the Spherical Pinch as a neutron generator.

(xxiv) A.M. Stoneham of A.E.R.E. Harwell, U.K. with R. Taylor on a book entitled "Handbook of Interatomic Potentials for Metals."

(xxv) During 1985, over 30,000 L of liquid helium were supplied on demand to six NRC divisions, three government departments, and three universities from the facility supervised by R. LeBreton and L.E. Erickson.

(xxvi) G. Bryant of McDonnel-Douglas with P. Kelly on hot-carrier dynamics in germanium.

(xxvii) R. Normandin has consulted for Bell Northern Research, Edmonton, Alberta, on the development of an external 1.2 GHz modulator for fibre optical communications.

(xxviii) R. Normandin is collaborating with M. Simard-Normandin in setting up a second harmonic DLTS type tunneling experiment in SiO_2 over Si tunnel junctions.

(xxix) P.B. Sewell is involved with the transfer of new electron source technology to Vickers Instruments of Ottawa for use in their wafer inspection scanning electron microscope.

(xxx) P.B. Sewell is collaborating on the development of a new LaB_6 cathode for the 25 MeV linear accelerator marketed by the Commercial Products Division of AECL.

(xxxi) P.B. Sewell conducted a study for Litton Systems on the permeation of helium from a gas discharge through thin aluminium membranes.

(xxxii) D. Landheer prepared Ta-Al composites whose properties are being analyzed by R. Timsit of Alcan Laboratories in Kingston.

(xxxiii) D. Landheer is working with R. Giles of Bell

Northern Research, Edmonton, Alberta, on channel waveguide couplers and modulators.

(xxxiv) K. Rajan and P.B. Sewell are collaborating with A. Rosenfeld of Alcan International Ltd. on composition modulated multilayer structures.

(xxxv) P.B. Sewell is the Principal Scientific Advisor and Internal Contact for the following Incubator projects: 1. Pyrotenax on parallel heating cable. 2. TPK Solar on silicon technology in the solar cell industry. 3. Epitek International on thin film resistors by magnetron sputtering. 4. Zontec Industries on the development of ozone generators and the measurement of ozone production.

D. COLLABORATIONS WITH UNIVERSITIES

The Division has extensive collaborations with universities both in Canada and throughout the world, to the mutual benefit of all parties. For Canadian universities we can provide access to some very sophisticated materials preparation and characterization facilities that require extensive infra-structure support. Our laboratories are increasingly used in a collaborative way for the training of graduate students. The division also provided work terms for eight undergraduate students in 1985.

The Si group of the MBE Section had the first eight of the following collaborations:

(i) SIMS depth profiling of Si MBE material. D. Johnston, University of Western Ontario, London, Ontario.

(ii) Quantitative SIMS analysis of Si-Ge superlattices. L. Lau and S. McIntyre, University of Western Ontario, London, Ontario.

(iii) MBE growth of Si through SiO_2 masks on (100) Si substrates for SOI devices. D. Waechter and G. Tarr, Carleton University, Ottawa, Ontario.

(iv) DLTS and Photoluminescence studies of Si grown by MBE. B. Hamilton, University of Manchester Institute of Science and Technology, Manchester, U.K.

(v) Resonant ion channeling in Si-Ge strained layer superlattices. W.K. Chu, Chapel Hill University, North Carolina.

(vi) "Round Robin" defect and impurity analysis of Si MBE material. R. Kubiak and E. Parker, City of London Polytechnic, London, U.K.

(vii) Photoluminescence study of Si grown by MBE. M. Thewalt, Simon Fraser University, Burnaby, British Columbia.

(viii) STEM microanalysis of Si-Ge superlattices. R. Piercy, McMaster University, Hamilton, Ontario.

(ix) The GaAs group of the MBE Section collaborated with S. Charbonneau of Simon Fraser University on time-resolved photoluminescence in GaAs.

(x) A. Sachrajda of Queen's University, Kingston, Ontario, has collaborated regularly on ongoing research projects with M. D'Iorio and his very low temperature expertise has been a benefit to the Quantum Hall Effect program.

(xi) N.E. Phillips and R. Fisher of the University of California at Berkeley are making magnetic and chemical measurements on some spin-glass samples provided by D.L. Martin after specific heat measurements were completed.

(xii) I.C. Khoo, Pennsylvania State University Electrical Engineering Department, visited R. Normandin several times re various experiments in infrared to visible image conversion using liquid crystals.

(xiii) L. Higginson of the Heart Institute of the University of Ottawa has undertaken a study of laser angioplasty where a laser is used to treat diseased arteries. During this period, an argon laser and a fibre delivery system were set up and operated at the University of Ottawa Animal Care Facility and a medical technician was trained in the use of the system in collaboration with L.E. Erickson and J.F. Froemel.

(xiv) S.M. Girvin, National Bureau of Standards, and M. Rasolt, Oak Ridge National Laboratory, collaborated on the theory of the fractional quantum Hall effect with A.H. MacDonald.

(xv) P. Bräunlich, Washington State University, collaborated with P. Kelly on laser interactions with solids.

(xvi) F. Grimaldi, Centre d'Etudes de Limeil-Valenton French Atomic Energy Commission, collaborated with M.W.C. Dharma-wardana on the theory of optical absorption in hot dense plasmas. Dr. Grimaldi visited the NRC during 22-28 August.

(xvii) F. Perrot of the Centre d'Etudes de Limeil-Valeton collaborated with M.W.C. Dharma-wardana on the theory of ion microfields. Dr. Perrot visited the NRC during 7-11 October.

(xviii) J. Dufty, University of Florida, Gainsville, Florida, collaborated with M.W.C. Dharma-wardana on statistical fluctuations and microfields in a degenerate electron gas.

(xix) G. Jaccuci of the University of Trento, Italy, collaborated with M.W.C. Dharma-wardana on the dynamic structure factor of one-component representations of charged fluids.

(xx) M.G. Cottam of the Physics Department, Essex University, U.K., with D.J. Lockwood on the excitations in magnetically ordered materials and superlattices. Dr. Cottam visited the Division for one month in February and again in May with support from the S.E.R.C., U.K., and the Nuffield Foundation.

(xxi) G.D. Jones and R.W.G. Syme of the Physics Department, Canterbury University, N.Z., with D.J. Lockwood on the vibrational and magnetic excitations of disordered solids.

(xxii) R.J. Nelmes of the Physics Department, Edinburgh University, U.K., and H. Arend of the Swiss Federal Institute of Technology with D.J. Lockwood on the ferroelectric transitions in lead hydrogen phosphate and lead deuterium phosphate.

(xxiii) G. Mischler and M.A. Renucci of the Laboratoire de Physique des Solides, associé au C.N.R.S., Toulouse, France, with D.J. Lockwood on the magnetic properties of transition metal halides and actinide semiconductors.

(xxiv) B. Briat of the Laboratoire d'Optique Physique, Equipe de Recherche du C.N.R.S. ER5, E.S.P.C.I., Paris, France, with D.J. Lockwood on the spectroscopic properties of solids.

(xxv) M.H. Kuok, Physics Department, National University of Singapore, with D.J. Lockwood on the vibrational spectra of ferroelectric materials. Dr. Kuok visited the Division for five months from June.

(xxvi) D. Neilson, University of New South Wales, Sydney, with R. Taylor and M.W.C. Dharma-wardana on the influence of correlations on the dielectric function of the electron gas.

(xxvii) A.B. Walker, University of East Anglia, Norwich, U.K., with R. Taylor on molecular dynamics simulations of phase diagrams in simple metals.

(xxviii) J. Ray, Clemson University, South Carolina, and A. Rahman, University of Minnesota, with R. Taylor

on molecular dynamics simulations of thermodynamic properties and nucleation in alkali metals and mixtures of alkali metals.

(xxix) P.K. John of the Department of Physics of the University of Western Ontario with E. Panarella on the application of the Spherical Pinch X-ray source for material studies.

(xxx) J.P. Vigier of the Institut Henry Poincaré of the Université Pierre et Marie Curie with E. Panarella to set up an experiment capable of discriminating between the predictions of the quantum potential theory and the effective photon hypothesis.

(xxxi) W.M. Honig of the University of Western Australia with E. Panarella on the organization of a N.A.T.O. Advanced Research Workshop to be held in Bridgeport, Connecticut, on June 23-27, 1986.

(xxxii) K. Vineberg and J. Morrison of McMaster University with P.H. Dawson on the application of secondary ion mass spectrometry to studies of surface structure. K. Vineberg carries out most of her graduate research in our laboratories.

(xxxiii) J.B. French of the Institute of Aerospace Studies of the University of Toronto with P.H. Dawson on quadrupole mass spectrometer technology.

(xxxiv) J. Corbett and F. Boswell of the University of Waterloo with K. Rajan on rigid body displacement at Epitaxial Interfaces.

(xxxv) G. Espérance of the École Polytechnique in Montreal with K. Rajan and P.B. Sewell on quantitative high voltage X-ray microanalysis.

(xxxvi) R. Egerton of the University of Alberta and T. Mallis of Energy, Mines and Resources with K. Rajan and P.B. Sewell on quantitative electron energy loss spectroscopy at high voltages.

(xxxvii) R. Egerton and P. Crozier of the University of Alberta with K. Rajan and P.B. Sewell on chemical interdiffusion at thin film interfaces.

D. EXTERNAL ACTIVITIES

The expertise of the Division is called upon in many different ways by outside organizations. This ranges, for example, from telephone consultation to the provision of in-depth advice to industry necessitating on-site visits. Funding agencies for academic research make considerable use of the Division's staff for review of proposals. Contributions to NSERC, in particular, are numerous and include those of several staff members who have served on site visit committees. Technical advice is provided to NRC's Technology Transfer Office. Finally there are contributions to the international scientific community and to the dissemination of technical information. Many papers and proposals are reviewed for scientific journals and other organizations. The highlights of these activities are described below.

(1) Honours

D.L. Martin was presented with the 1985 Huffman Memorial Award, in recognition of contributions to thermochemistry and thermodynamics, at the 40th Annual Calorimetry Conference at Asilomar, California.

E. Panarella was elected Fellow of the New York Academy of Sciences in recognition of outstanding scientific achievements in plasma physics.

(2) Industrial Programs

P.H. Dawson was a scientific advisor on a PILP program to Sciex Inc. concerning trace impurity analysis.

A. Szabo was scientific advisor on IRAP program #CA910-5-0842.

D.J. Lockwood was an advisor to the RCMP on laser applications.

P.B. Sewell is Scientific Liaison Officer for the following contracts: 1. PILP project with Pyrotenax Canada Limited for the development of a semiconductor based parallel heating cable. 2. PILP project Waterloo Scientific for the development of a scanning laser microscope. 3. NSERC project with Corona Coaters (Vancouver) for sputtered thin film magnetic storage devices. 4. DSE contract with Varian Canada Inc. on the development of long life thermionic emitters for high power Klystron tubes for satellite communication.

D. Landheer is Liaison Officer for the following contracts: 1. NSERC project CRD-8501 entitled "Oxide Film Substrates and Devices". 2. PILP Contract 685 entitled "Rotating Magnetron Sputtering Source".

(3) Seminars Given

A. MacDonald gave seminars at IBM, Yorktown Heights; the Max-Planck Institute, Grenoble, France; the Ecole Normale Superière, Paris, France; University of Manitoba, Winnipeg, Manitoba; Memorial University of Newfoundland, St. John's, Newfoundland; and at Queen's University, Kingston, Ontario.

L.E. Erickson gave a seminar at Queen's University, Kingston, Ontario.

M.W.C. Dharma-wardana gave seminars at L'Université Paris-Sud, Orsay, France, and at The Institute of Fundamental Studies, Colombo, Sri Lanka.

E.W. Fenton gave seminars at Simon Fraser University, Burnaby, British Columbia, and at Exxon Laboratories, Annandale, New Jersey.

R. Taylor gave a series of three lectures at the University of East Anglia, Norwich, and seminars at A.E.R.E. Harwell, Imperial College, London, University of Hamburg, University of Münster, and Queen's University, Kingston, Ontario.

D.J. Lockwood gave a seminar at the University of Kyoto, Japan.

P. Dawson taught a course on Ion Optics sponsored by the American Society for Mass Spectrometry.

P.T. Coleridge gave seminars at the Universities of Sussex, Leeds, and Norwich.

J.F. Young gave a seminar at Northern Telecom.

E. Panarella gave seminars at the Foundation Louis de Broglic, Paris, and at Imperial College, London.

R. Normandin gave a seminar at the Bell Northern Research Laboratory in Edmonton, Alberta.

E.V. Kornelsen gave seminars at the University of Western Ontario, London, Ontario, and at the Catalysis Discussion Group at Carleton University, Ottawa, Ontario.

(4) Invited Talks at Conferences

P.H. Dawson at the American Vacuum Society Annual Symposium in Houston and at a Conference on Residual Gas Analysers sponsored by the National Bureau of Standards, Washington, D.C.

D.J. Lockwood at the International School of Atomic and Molecular Spectroscopy, Erice, Italy.

A. MacDonald at the Canadian Association of Physicists meeting in Fredericton, New Brunswick.

A. Szabo at the Canadian Association of Physicists Workshop on Modern Lasers and Applications, Toronto, Ontario.

P. Bräunlich and P. Kelly at the International Conference on Exoemission and Applications, Osaka, Japan.

D.L. Martin gave the Huffman Award Lecture at the 40th Annual Calorimetry Conference, Asilomar, California.

E.V. Kornelsen at Surface Canada, Fredericton, New Brunswick, June 1985.

(5) Committees and Boards

G.C. Aers was a member of the NSERC Major Installation grant committee for computer installation, a member of the NRC Electronic Data Processing Committee, and chairperson of the NRC FPS 264 Users Group.

R. Taylor is chairman of the organizing committee for the CAP-NATO summer school on Interfaces, Quantum Wells and Superlattices to be held in Banff, Alberta, August 16-29, 1987. He is also vice-chairman of the Theoretical Physics Division of the Canadian Association of Physicists.

D.J. Lockwood served on the Technical Review Committee of the Division of Physics. Also, he is a member of the organizing committee for the Advanced Research Workshop on Common Themes in Ferroelectric Crystals and Liquid Crystals to be held in Boulder, Colorado.

E.V. Kornelsen is a member of the Interdivisional Committee on Research Associates. He is also a member of the Planning Committee for McMaster University Microelectronic Centre and a member of NSERC site visit committees to Université de Sherbrooke and McMaster University.

P.H. Dawson is a Member of the Editorial Board of the International Journal of Mass Spectrometry and Ion Processes. He was also a member of an NSERC Site visit committee on an Industrial Chair in Electro-optical materials at McMaster University.

A.H. MacDonald was a member of the Colloquium Committee of the Division of Physics.

J.G. Cook served as scientific secretary to the Physics Committee of NSERC, and is on the editorial board of Physics in Canada.

(6) Visits Elsewhere

R. Taylor visited the University of East Anglia, Norwich, U.K., for two weeks and A.E.R.E. Harwell, U.K., for four weeks where he worked on the beginning stages of a book in collaboration with A.M. Stoneham.

P.T. Coleridge was at the University of Sussex from August 1984 to August 1985 working with Prof. Springford on heavy Fermion systems and exchange enhanced paramagnets. The collaboration will continue using the high field (15 T) low temperature (30 mK) dHvA spectrometer being developed there.

M. D'Iorio has visited Oxford Instruments (England) to oversee the testing of the dilution refrigerator purchased by NRC.

M. D'Iorio has visited the Electrotechnical Laboratory (ETL) in Tsukuba and Gakushuin University in Tokyo, Japan, where research on the quantum Hall effect is in progress.

M. D'Iorio visited the Naval Research Laboratory (Washington) in the framework of an ongoing collaboration on Si-MOSFET with this institution. Also visited the National Bureau of Standards (Washington) where a similar very-low-temperature - high-magnetic-field facility is being established.

A. MacDonald visited l'École Normale Supérière, Paris, under the CNRS/NRC agreement on cooperative research.

I.M. Templeton visited Dr. G. Lonzarich and Prof. D. Shoenberg at the Cavendish Laboratory, Cambridge, U.K.

P.H. Dawson visited K. Standish of the University of Manitoba, Winnipeg, Manitoba, to discuss time-of-flight mass spectrometers.

M.W.C. Dharma-wardana visited CECAM, Faculté des Science, Orsay, France. He has a collaborative research program with F. Grimaldi and F. Perrot of the French Atomic Energy Commission on strongly coupled electron-ion systems at high temperatures.

D.L. Martin visited Prof. N.E. Phillips at the University of California, Berkeley, to discuss the spin-glass problem.

E.W. Fenton visited the Physics Department at the University of British Columbia, Vancouver, British Columbia.

F. DIVISIONAL ORGANIZATION AND PERSONNEL DIRECTORY

The Division is organized administratively into sections and groups as listed below. The research activities are cross-referenced to the appropriate parts of Section B.

(a) Administration

Director	Dr. M.J. Laubitz	993-1053
Assistant Director	Dr. J.P. Hobson	993-9196
Secretaries	J. Perratt	993-9880
	S. Routliff	993-9196
	J. Zahab	993-2046

(b) Quantum Microphysics

	Research Activities
Head: Dr. P.H. Dawson 993-9405	2(d),5(i),11(b)
Dr. R.A. Armstrong	5(a),(e)
D.L. Blair	5(a)
O.M. Bolduc	
D.J. Brown	4(a)
Dr. J.G. Cook	1(b),5(j),6(e),(f)
Dr. M. D'Iorio	4(a)
Dr. J.E. Hulse	5(a),(c),(d)
Dr. P.J. Kelly	6(d)
B.A. Kettles	2(a),(b),(f),6(a), 7(c)
H.J. Labbé	2(c),6(b)
Dr. D.J. Lockwood	2(c),4(d),6(b)
B.F. Mason	5(f)
Dr. R. Normandin	1(c),2(e),(f),(g), 5(g),(n),6(a),(c), 7(a),(b),(c),(d)
Dr. N. Ohno	6(b)
G.W. Richardson	2(d),5(i),11(b)
S. Rolfe	2(d)
P. van der Meer	1(b),6(e),(f)
Dr. B.R. Williams	5(f)

	Research Activities
Dr. J. Young	2(a),(b),(d),5(g), 5(n),6(a),7(d),9(g)
K. Vineberg (guest)	5(i)

(c) Condensed Matter

Head: Dr. E.W. Fenton 993-9392	4(e),8(a),(b)
Dr. G.C. Aers	2(1),4(b),(e),5(b), 5(j),6(e),(f),8(a), 10(b),(c)
Dr. C. Dharma-wardana	4(b),(d),9(e),(f), 10(b),(c)
	Research Activities
Dr. C.R. Leavens	5(b),(h)
Dr. A.H. MacDonald	4(b)
Dr. H.C.A. Oji	4(b)
Dr. R. Taylor	9(e),10(a),(b),(c)

(d) Molecular Beam Epitaxy

Head: Dr. E.V. Kornelsen 993-1123	1(a)
Dr. J-M. Baribeau	1(a)
R. Coté	
R. Chapman	
Dr. M.W. Denhoff	1(a)
Dr. R.L.S. Devine	1(a)
D. Elliott	
Dr. D.C. Houghton	1(a)
Dr. P. Maigné (guest)	1(a)
Dr. W.T. Moore	1(a)

(e) Microscopy and Microfabrication

Head: Dr. P.B. Sewell 993-2304	2(h),(i),(j),(k), 2(l),(m),(n),5(k), 5(l),(m),(n)
Dr. M. Buchanan	3(a),(b)

	Research Activities
Dr. A. Delage	2(h),(n)
Dr. P.L. Janega	
Dr. D. Landheer	1(f),3(a),(b)
J. LeGeyt	
J. McCaffrey	
Dr. K. Rajan	1(d),(e),2(h),(i), 2(j),(k),(l),(m), 5(k),(l),(m),(n)
R.W. Stewart	
E.A. Vilks	3(a),(b)

(f) Electronic Structure and Calorimetry

Head: Dr. I.M. Templeton 993-7093	4(c),9(d),11(f)
R. Boulet	11(e)
Dr. P.T. Coleridge	9(a),(b),(c),11(e)
G.P. Green	
Dr. F.R. Lipsett	11(d)
Dr. D.L. Martin	11(a)

(g) Quantum Electronics

Head: Dr. A. Szabo 993-1122	7(e),(f),(g)
Dr. L.E. Erickson	7(h)
J.F. Froemel	
R. LeBreton	

(h) Dr. E. Panarella 993-2731	3(c),11(c)

G. PUBLICATIONS DURING 1985

1. Armstrong, R.A. and Egelhoff, W.F., Jr. "An Analysis of Angular Dependent XPS Peak Intensities", Surf. Sci. 154, L2225-L232.
2. J.G. Cook "Evaporated Epitaxial Chromium Films", Thin Solid Films, 129, L57.
3. J.G. Cook and G.H. Fritsch "Thermal Conductivity in the Liquid Phase Chapter" in "Handbook of Thermodynamic and Transport Properties of Alkali Metals" (Ed. R.W. Ohse), Blackwell.
4. P.T. Coleridge "Impurity Resistivities in Copper", J. Phys. F: Metal Phys. 15, 1727.
5. P.H. Dawson "Low Energy Collison-Activated Dissociation of n Butylbenzene: Effect of Electron Energy used During Parent Ion Formation", Int. J. Mass Spectrom. Ion Proc. 63, 337.
6. P.H. Dawson and Wing-Fung Sun "The Collison Induced Dissociation of O_2^- Studied using a Triple Quadrupole Mass Spectrometer", Int. J. Mass Spectrom. Ion Proc. 61, 123.
7. P.H. Dawson "Collisionally Activated Dissociation of O_2^+ and the Role of Excited States", Int. J. Mass Spectrom. Ion Proc. 63, 305.
8. P.H. Dawson "Performance Characteristics of an rf-only Quadrupole", Int. J. Mass Spectrom. Ion Phys. 67, 267.
9. M.W.C. Dharma-wardana and F. Perrot "Embedding an Ion-Atom in a Plasma: Influence of the Host Plasma on the Photo-Effect", Phys. Rev. A31, 970.
10. F. Grimaldi, A. Grimaldi-Lecourt and M.W.C. Dharma-wardana "Time Dependent Density Functional Theory of Light Absorption in Dense Plasmas", Phys. Rev. A32, 1063.
11. F. Perrot and M.W.C. Dharma-wardana "An All-Order Resummation of the Baranger-Mozer Series", Physica A (Statistical Physics), 134, 231.
12. K.K. Sharma and L.E. Erickson "Optically Detected Nuclear Magnetic Resonance of $LiYF_4:Eu^{3+}$ in the Ground Electronic State $^7F_0$", J. Phys. C: Solid State Phys. 18, 2935.

13. L.E. Erickson "NMR Measurement of an Ion in an Excited State by Indirect Optical Detection: A $^1G_4$ Level of $LiYF_4:Pr^{3+}$", Phys. Rev. B32, 1.
14. L.E. Erickson "NMR Measurement of a Rare Earth Ion in an Excited State by Indirect Optical Detection", Laser Spectroscopy VII, ed. by T.W. Hansch and Y.R. Shen, Springer-Verlag (Berlin).
15. E.W. Fenton "Cooper Pairing in the Presence of Inhomogeneous Magnetism", Prog. Theor. Phys. (Kyoto), 80, 94.
16. E.W. Fenton "Proximity and Josephson Effects with Heavy-Fermion Superconductors", Physica, 135B, 60.
17. E.W. Fenton and G.C. Aers "Upper Critical Field of a Superconductor with Arbitrary Spin-Orbit Scattering: $CeCu_2Si_2$ and UBe_{13}", Solid State Comm. 56, 337.
18. E.W. Fenton and G.C. Aers "Theory of Infrared Conductivity from Density Waves: $(TMTSF)_2X$", Molecular Crystals and Liquid Crystals, 119, 201.
19. E.W. Fenton "Lowest Energy Cooper Pairing in the Presence of Antiferromagnetism", Solid State Comm. 54, 633.
20. E.W. Fenton "Correlations and Spin Susceptibility of Lowest Energy Cooper Pairing in an Antiferromagnet", Solid State Comm. 56, 1033.
21. E.W. Fenton "Impurity Effects on Lowest Energy Cooper Pairing in an Antiferromagnet", Solid State Comm. 57, 241.
22. E.W. Fenton "Mixed Spin-Singlet and Spin-Triplet Cooper Pairing Caused by Inhomogeneous Magnetism", Solid State Comm. 53, 501.
23. E.W. Fenton "Proximity and Josephson Effects for Heavy-Fermion Superconductors", Solid State Comm. 54, 709.
24. S. Suzuki, G.C. Weatherly and D. Houghton "The Response of Carbonitride Particles in HSLA Steele to Weld Thermal Cycles", Acta Metallurgica, in press.
25. A. Abtahi, P. Bräunlich, P. Kelly and J. Gasiot "Laser Stimulated Thermoluminescence", J. Appl. Phys. 58, 1626.

26. M. Fontaine and E.V. Kornelsen "The Effect of a Depth Dependent Diffusion Coefficient on the Trapping of Mobile Particles Near a Solid Surface", Radiat. Eff. 90, 111.
27. C.R. Leavens and D.S. Ritchie "Extension of the N-point Padé Approximants Solution of the Eliashberg Equations to $T \sim T_c$", Solid State Commun. 53, 137.
28. C.R. Leavens "Effect of Thermal Smearing on the Electron-Phonon Spectral Function Obtained by Inversion of Normal Metal Tunnelling Data", Solid State Commun. 54, 625.
29. C.R. Leavens "Effect of a Weak Momentum Dependence in the Electron Self-Energy Conductance of a Normal Metal - Insulator - Normal Metal Tunnelling Junction", Solid State Commun. 55, 13.
30. C.R. Leavens "Anderson Localization and Universal Degradation of T_c in High-Temperature Superconductors", Phys. Rev. B31, 6072.
31. C.R. Leavens and B. Mitrovic "Effect of Sharp Structure in the Electron Density of States on the Electron-Phonon Spectra Function Obtained by Inversional of Normal Metal Tunnelling Data", Physica 135B, 208.
32. M.G. Cottam and D.J. Lockwood "One-Magnon Raman Scattering in a S = 5/2 Antiferromagnet", Phys. Rev. B31, 641.
33. A. Zwick, G. Nouvel, M.A. Renucci, G. Mischler, W. Suski and D.J. Lockwood "Raman Scattering in Magnetic US_3", Solid State Commun. 53, 783.
34. D.J. Lockwood, R.W.G. Syme and B. Briat "Raman Spectrum of Binuclear $Cs_3Ru_2Cl_9$", J. Phys. C: Solid State Phys. 18, 1721.
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Magnetic Field", Phys. Rev. B32, 2291.

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55. E. Panarella "Diffraction of Statistically Independent Photons from a Laser Source: Photon Counting on the Diffraction Pattern", Spec. Sc. Tech. 8, 35.
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57. K. Rajan "Weak Beam Imaging of Coherent Twin Boundaries after High-Temperature Deformation", Proc. 43rd Annual Meeting EMSA, p. 242, San Francisco, Phys. ed. G.W. Bailey, San Francisco, CA.
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61. N.H. March, R.C. Perrin and R. Taylor "Topology of the Fermi Surface and the Calculation of the Phase Diagram of Lithium by Variable Cell Molecular Dynamics", Solid State Comm. 53, 287.
62. R. Taylor "Simulation Techniques and Potentials for Metals", Physica, 131B, 103.
63. R. Taylor "Pair Potentials and their Limitations for Computer Simulations", J. de Phys. 46, C4-309.

64. I.M. Templeton "Fermi Surface Changes and Electron Scattering Anisotropy in the Potassium-Rubidium Alloy System", J. Low Temp. Phys. 60, 85.
65. H.M. van Driel, J.E. Sipe and Jeff F. Young "Laser Induced Coherent Modulation of Solid and Liquid Surfaces", J. Lumin. 30, 446.
66. J.E. Sipe, H.M. van Driel and Jeff F. Young "Surface Electrodynamics: Radiation Fields, Surface Polaritons, and Radiation Remnants", Can. J. Phys. 63, 104.
67. Jeff F. Young "The Influence of Material Response on the Properties of Laser-Driven Grating Linear Accelerator Structures", Particle Accelerators, 18, 23.
68. Jeff F. Young, H.R. Jensen and Martine Simard-Normandin "A Simple, Non-Destructive Optical Technique to Characterize Ion-Implanted Semiconductor Wafers", in Rapid Thermal Processing, T. Sedgwick, T. Siedel and B. Tsour (eds.).

Oral Presentations at Conferences
(Invited Talks were listed in Section E)

R.A. Armstrong "Incidence Dependent Auger Electron Spectroscopy", 45th Annual Conference on Physical Electronics, University of Wisconsin, Milwaukee, June.

J.G. Cook and M.P. van der Meer "Optical Properties of Sputtered Co_3O_4 Films", American Vacuum Society National Symposium, Houston, November 19-22.

M.W.C. Dharma-wardana "Ion Microfields in Plasmas", Williamsburg, Virgina, U.S.A. International Meeting on Hot Dense Plasmas, October.

M.W.C. Dharma-wardana "Time Dependent Density Functional Theory of Light Absorption in Plasmas", Williamsburg, Virginia, U.S.A. International Meeting on Hot Dense Plasmas, October.

L.E. Erickson "RF-optical spectroscopy of Rare-earth Ions in Insulating Solids. Department of Physics, Queen's University, Kingston, Ontario. March 20

L.E. Erickson "NMR Measurement of a Rare Earth Ion in an Excited State", Seventh Int. Conf. on Laser Spectroscopy, Kaanapali, Hawaii, June 24-28.

R. Mallard, D.C. Houghton and G.J.C. Carpenter "Defects in LPCVD Polycrystalline Si", Kingston Metal Physics Conference, June.

G.J.C. Carpenter, R. Mallard and D.C. Houghton "Some Applications of Electron Microscopy to Studies of Semiconductor Materials", Kingston Metal Physics Conference, June.

M. D'Iorio and B.M. Wood "The Temperature Dependence of the Quantum Hall Resistance", Electronic Properties of Two-Dimensional Systems VI, Kyoto, Japan, September.

M.G. Cottam and D.J. Lockwood "One-Magnon and Two-Magnon Raman Scattering from MnF_2", International Conference on Magnetism, San Francisco, August.

D.J. Lockwood, N. Ohno, R.J. Nelmes and H. Arend "The Lattice Statics and Dynamics of Ferroelectric $PbHPO_4$", International Meeting on Ferroelectricity, Kobe, August.

D.J. Lockwood "Spectroscopy of the $KZnF_3$:Co Vibronic Laser", International School of Atomic and Molecular Spectroscopy, Erice, June.

P.M. Platzman, S.M. Girvin and A.H. MacDonald "Disorder and the Fractional Quantum Hall Effect", APS March Meeting, Baltimore, MD.

D.L. Martin "Use of ANCOM 15C-3a Amplifiers for Adiabatic Shield Control", 40th Annual Calorimetry Conference, Asilomar, California, August.

D.L. Martin "Recent Experiments on Spin-Glasses", 40th Annual Calorimetry Conference, Asilomar, California, August.

I.C. Khoo and R. Normandin "Infrared to Visible Conversion Using Four Wave Mixing in a Liquid Crystal Film", Published in the Technical Digest of the Conference on Lasers and Electrooptics, Baltimore, May 21-24.

E. Panarella and V. Guty "The REXIMPLO Spherical Pinch: Progress Report on the Construction of the Machine and Preliminary Testing", 27th Annual Meeting of the Division of Plasma Physics of the A.P.S., San Diego, California, November.

P. Savic and E. Panarella "The Spherical Pinch as a Source of Soft X-rays for Microlithography", 27th Annual Meeting of the Division of Plasma Physics of the A.P.S., San Diego, California, November.

K. Rajan and J. McCaffrey "A TEM Study of Thin Film Interactions in Bi-Metallic Couples", TMS-AIME Fall Meeting, Toronto, October 15.

K. Rajan "The Role of Coherent Interphase Boundaries on Deformation", TMS-AIME Fall Meeting, Toronto, October 15.

A. Szabo "On-Axis Photon Echo Modulation in Ruby", Gordon Conference on Nonlinear Optics and Lasers, Wolfeboro, NH, July 28 - August 2.

R. Taylor "The Use of Liquid Metal Structure Factors in Determining Interatomic Potentials in Metals", March Meeting of the A.P.S., Baltimore.

Jeff F. Young, H.R. Jensen and Martine Simard-Normandin "A Simple, Non-Destructive Optical Technique to Characterize Ion-Implanted Semiconductor Wafers", Materials Research Society Meeting, Symposium on Rapid Thermal Processing, Boston, MA, December.

H. PATENTS

1. A. Szabo, Fast Input/Output Technique using Stark Shifting for a Frequency Selective Optical Memory. Canadian Patent #1,197,009. Issued November 19, 1985.

2. A patent application was filed by P.H. Dawson for a quadrupole mass spectrometer with modulated fields.